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WAVE FORCES ON A HORIZONTAL CIRCULAR CYLINDER

by

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13. ABSTRACT

A horizontal circular cylinder, located near the floor of a two dimensional wave channel, was subjected to a train of gravity waves. The wave height and horizontal and vertical forces on the cylinder due to the incident waves were measured and presented in dimensionless form. Experimental values of the horizontal and vertical dimensionless force coefficients are presented as functions of relative wave height and relative wave length. The dimensionless force coefficients predicted by a modified Morrison's equation are compared with the experimental data. Experimental wave lengths of from two to seventeen feet were investigated.

The horizontal force coefficients were found to vary linearly with wave height over the range of wave lengths tested. The vertical force coefficients displayed regions in which the force was both inertia dominated by a lift force.

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Wave Forces on a Horizontal Circular Cylinder

by

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LIST OF SYMBOLS

Symbol	Quantity	Units	Dimension
a	Radius of Cylinder	ft	L
b	Cantilever Base Dimension	ft	L
C_d	Drag Coefficient	-	-
C_L	Lift Coefficient	-	-
C_m	Added Mass Coefficient	-	-
E	Modulus of Elasticity	lb/ft^2	F/L^2
F_x	Horizontal Force	lb	F
$F_{x\ max}$	Maximum Horizontal Force	lb	F
f_x	Horizontal Force Coefficient	-	-
F_y (+) (-)	Vertical Force (Upward) (Downward)	lb	F
$F_{y\ max}$	Maximum Vertical Force	lb	F
f_y (+) (-)	Vertical Force Coefficient (Upward) (Downward)	-	-
g	Acceleration of Gravity	ft/sec^2	L/T^2
h	Water Depth	ft	L
H	Wave Height	ft	L
h_b	Cantilever Beam Height Dimension	ft	L
k	Wave Number $(2\pi/L)$	1/ft	1/L
K	Stiffness	lb/ft	F/L
L	Wave Length	ft	L
ℓ	Length of Cylinder	ft	L
ℓ_b	Cantilever Beam Length Dimensi...	ft	L

P	Cantilever Load	lb	F
t	Time or Duration	sec	T
T	Wave Period	sec	T
u	Velocity in X-direction	ft/sec	L/T
$\dot{u}$	Local Acceleration	ft/sec^2	L/T^2

ε	Strain	ft/ft	-
ρ	Mass Density	lb-sec^2/ft^4	F-T^2/L^4
μ	Fluid Viscosity	lb-sec/ft^2	F-T/L^2
σ	Wave Angular Frequency	1/sec	1/T
Φ	Velocity Potential	ft^2/sec	L^2/T

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I. INTRODUCTION

Exploration of the ocean floor has received increased interest in the past several decades, particularly the area of the continental shelf. A significant amount of attention has been devoted to offshore oil exploration, to the recovery of petroleum and to deployment of undersea habitats. Often petroleum is located in remote areas of the world and oil production involves use of very large submerged oil storage tanks and associated pipelines. In other locations petroleum has been piped ashore, through the surf zone, to shore facilities. Recently, interest has been demonstrated [1] in the deployment of large submerged nuclear power plants. In the reference cited it is proposed that a nuclear plant be placed on the ocean floor in two hundred and fifty feet of water.

As one might expect, this activity has generated considerable interest in the interaction of gravity waves with submerged objects. For example, the wave force exerted on vertical piling has been a topic of many investigations during the past twenty years [2], [3], [4]. In these studies the well known Morrison Equation [4] appears to be the most practical approach to the calculation of wave forces. This equation combines both a drag and inertia term, the values of which must be determined experimentally. At best, these two experimental coefficients are dependent upon the geometry of the pile and amplitude of the fluid motion, and it would appear that twenty years of research has only partially delineated this interdependence.

In the case of large, deeply submerged objects the Morrison Equation is also applicable and generally yields valid results for the horizontal wave forces provided diffraction effects do not become appreciable. In this instance, the drag term may be discarded since the hydrodynamic force

is primarily inertial in nature. However, it is still necessary to know the added mass coefficient as it depends on the body configuration and the effect of the rigid bottom surface. Moreover, if the object is bottom mounted the vertical fluid acceleration is zero, and accordingly, the Morrison Equation yields zero vertical force, a result that is obviously invalid.

A diffraction theory, valid for the calculation of forces exerted on large submerged or semi-submerged bodies of arbitrary shape, which accounts for both the effect of the free surface and bottom, has been developed by Garrison and Chow [5]. Theoretical results were compared with corresponding experimental results for two different practical submerged tank configurations and good agreement was found. However, the method is valid for linear incident waves only; the nonlinear effects of large amplitude waves can not be determined.

In the case of large objects, which are not so deeply submerged that the free surface has a sizable effect, no theory is available which is valid for large values of wave height and few experimental results have been published. However, one study has been carried out by Johnson [6] for horizontal wave forces acting on a bottom-mounted, horizontal circular cylinder in long waves. Inasmuch as only long waves were considered, the results were dependent on the wave height and water depth only and no consideration was given to intermediate wave lengths. Moreover, rather than correlate the forces with appropriate dimensionless parameters, Johnson used a regression analysis to correlate the forces. Consequently, little light was shed on the basic mechanism involved.

Schiller [7] measured wave forces acting on a submerged horizontal circular cylinder due to rather small amplitude waves. Over the range of wave heights considered in his tests, he found the amplitude of the horizontal force to vary linearly with the wave height. At small wave heights the vertical force was found to vary harmonically with the wave motion, the maximum amplitude of which increased linearly with the wave height. At larger values of wave height, the vertical force amplitude tended to increase in proportion to the wave height squared. This latter variation of the wave force is caused by the velocity squared term occuring in Bernoulli's Equation.

The present investigation was an extension of Schiller's work to include large wave heights. However, the present investigation was limited to the single configuration where the horizontal circular cylinder was placed on the bottom. A transition section was placed in the wave channel used by Schiller, at a location twenty feet from the wave generator for purposes of providing a natural transition from intermediate or deep water waves to shallow water waves of finite amplitude. The beach slope was adjusted for negligible reflection as discussed in the section on experimental apparatus.

II. THEORETICAL ANALYSIS

The problem under consideration is depicted in Figure 1. A train of regular waves of height H is considered to progress in the positive x direction in water of depth h. It is the present interest to determine the horizontal and vertical components of wave force acting on the horizontal circular cylinder in contact with the rigid bottom.

The exact analytical solution to this problem is extremely difficult and, therefore, only an approximate analysis is attempted. However, it is first instructive to carry out a dimensional analysis of all of the pertinent parameters. It is known *a priori* that the maximum horizontal or vertical force per unit length of a cylinder is dependent upon the following variables:

$$\frac{F_{x\,max}}{\ell} \text{ or } \frac{F_{y\,max}}{\ell} = f(h,a,L,H,\rho,g,\mu) \tag{1}$$

in which

H = wave height
ℓ = cylinder length
h = water depth
a = cylinder radius
L = wave length
ρ = fluid density
g = gravitational acceleration
μ = fluid viscosity.

It may be noted at this point that a relationship exists between the parameters associated with the incident wave (i.e., H, T, L and h, where T denotes the period). Consequently, only three of the incident wave parameters are needed in the dimensional analysis, i.e., either H, h and L or H, h and T. Moreover, either of these three sets of parameters

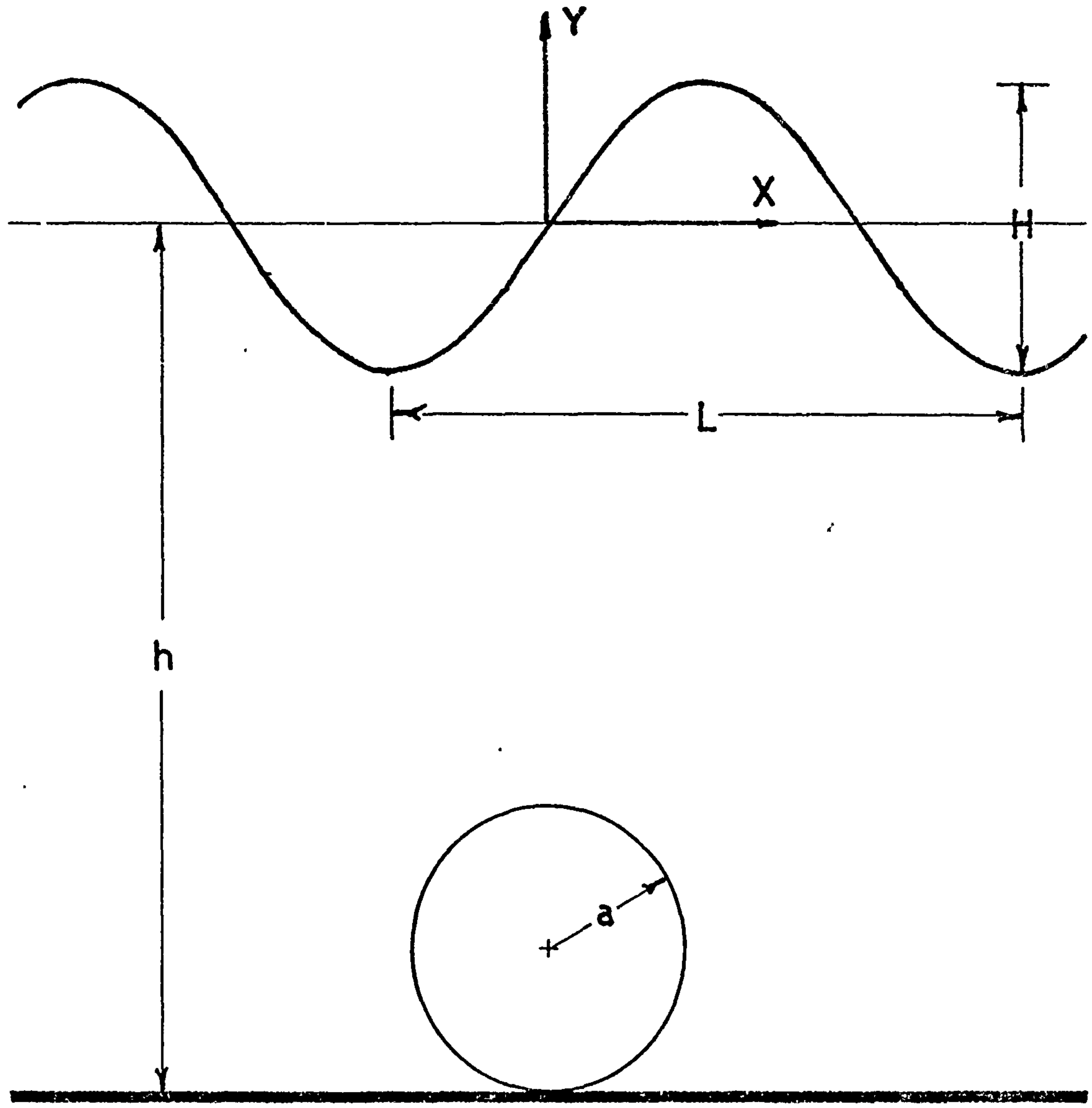


FIGURE 1 DEFINITION SKETCH

completely describes the incident wave regardless of whether or not it is of small amplitude. For small amplitude waves the well-known relationship

$$\frac{2\pi}{gT^2} = \frac{1}{L} \operatorname{Tanh} \frac{2\pi h}{L} \tag{2}$$

exists between the parameters which describe the incident wave. For waves of finite amplitude the relationship is more complicated but nevertheless exists.

A dimensional analysis of the physical paramaters indicated in Equation (1) gives the following dimensionless parameters.

$$\frac{F_{x\ max}}{\rho g a^2 \ell} \text{ or } \frac{F_{y\ max}}{\rho g a^2 \ell} = f\left(\frac{2\ell a}{L}, \frac{h}{a}, \frac{H}{2a}, \frac{\mu}{\rho\sqrt{gha^2}}\right) \tag{3}$$

As pointed out by Garrison and Chow [5] the last term on the right hand side of Equation (3) represents the ratio of the Froude number to Reynolds number and, accordingly, is an indicator of the ratio of the viscous to gravity forces. If this number is small, corresponding to large scale flows with small viscosity, it may be assumed that this parameter may not be important since the flow would be controlled primarily by gravitational forces. In this case Equation (3) may be written as

$$\frac{F_{x\ max}}{\rho g a^2 \ell} \text{ or } \frac{F_{y\ max}}{\rho g a^2 \ell} = f\left(\frac{2\pi a}{L}, \frac{h}{a}, \frac{H}{2a}\right) \tag{4}$$

However, as noted previously, the wave period may be used in place of the wave length, in which case Equation (4) would appear in alternate form as

$$\frac{F_{x\,max}}{\rho g a^2 \ell} \text{ or } \frac{F_{y\,max}}{\rho g a^2 \ell} = f\left(\frac{gT^2}{h}, \frac{h}{a}, \frac{H}{2a}\right) \tag{5}$$

Equation (5) may also be written in a third form as

$$\frac{F_{x\,max}}{\rho g a^2 \ell} \text{ or } \frac{F_{y\,max}}{\rho g a^2 \ell} = f\left(\frac{gT^2}{h}, \frac{gT^2}{H}, \frac{h}{a}\right). \tag{6}$$

In the experimental program an attempt is made at determining the correlation of the dimensionless parameters, on the right hand side of Equations (4), (5) and (6), with the force coefficients.

The complete analytical solution to the wave interaction problem is quite complex. However, by use of Morrison's Equation [4], an approximate representation may be carried out. For this purpose, the velocity potential associated with the incident wave is written as

$$\phi = \frac{H}{2} \frac{g}{\sigma} \frac{\cosh k\,(y+h)}{\cosh kh} \cos(kx - \sigma t) \tag{7}$$

where $k = 2\pi/L$ denotes the wave number and $\sigma = 2\pi/T$ denotes the frequency. From Equation (7) the horizontal component of velocity and acceleration is obtained, respectively, by differentiation as,

$$u = -\frac{H}{2} \frac{gk}{\sigma} \frac{\cosh k(y+h)}{\cosh kh} \sin(kx - \sigma t) \tag{8}$$

$$\dot{u} = \frac{H}{2} gk \frac{\cosh k(y+h)}{\cosh kh} \cos(kx - \sigma t) \tag{9}$$

The horizontal force acting on the cylinder is written, according to Morrison's Equation, as

$$Fx = \frac{C_d}{2} \rho\, 2a\ell\, u^2 + (1 + C_m)\pi a^2 \ell \dot{u} \qquad (10)$$

where C_d denotes the drag coefficient and C_m denotes the added mass coefficient. However, for cases where the particle motion is small in comparison to the cylinder diameter separation effects are small and it is possible to disregard the drag contribution to the total force and write Equation (10) as

$$\frac{F_x}{\rho g a^2 \ell} = (1 + C_m)\ \pi k\, \frac{H}{2}\, \frac{\mathrm{Cos}\ (\sigma t)}{\mathrm{Cosh}\ kh} \qquad (11)$$

Using the definition of k and σ, Equation (11) may be written in terms of the dimensionless parameters indicated in Equation (4) as

$$\frac{F_{x\ max}}{\rho g a^2 \ell\, (H/2a)} = (1 + C_m)\ \frac{2\pi a}{L}\, \frac{\pi}{\mathrm{Cosh}\ (\frac{2\pi a}{L}\frac{h}{a})} \qquad (12)$$

The vertical component of the force could be expressed in a form similar to Equation (10), but the vertical component of acceleration on the bottom is zero. It is supposed, therefore, that the vertical component of force is associated with the lift force only. Accordingly the vertical force may be written as

$$F_y = \frac{\rho}{2} u^2\, C_L\, 2a\ell \qquad (13)$$

in which C_L denotes the lift coefficient and u the wave induced particle velocity on the bottom. Substituting for the velocity from Equation (8), Equation (13) may be written as

$$\frac{Fy}{\rho g a^2 \ell} = 2\, C_L \left(\frac{2\pi a}{L}\right) \left(\frac{H}{2a}\right)^2 \frac{\sin^2 \sigma t}{\sinh 2kh} \qquad (14)$$

Equations (12) and (14) contain two coefficients, namely the added mass coefficient, C_m, and the lift coefficient, C_L. Values for those coefficients which account for both the bottom and free surface are not available in the literature. However, if the water is relatively deep the free surface effect should be small. In this case the exact potential flow value for a circular cylinder in contact with the rigid bottom has been calculated by Garrison [8] as

$$C_m = 2.29.$$

For the same geometry, Daltman and Helfinstein [9] have calculated the lift coefficient by an approximate method. Their value is

$$C_L = 4.48.$$

These values of the two coefficients may be used in Equations (12) and (14) to obtain approximate expressions for the horizontal and vertical force coefficients. It should be noted, however, that the assumptions underlying these approximate relationships are met only when the scale of the waves, i.e., the wave length and water depth are large in comparison to the cylinder diameter. Moreover, since linear wave theory has been used to determine the velocity and acceleration, the validity is also restricted to small amplitude waves.

III. DESCRIPTION OF APPARATUS AND EXPERIMENTAL PROCEDURE

A. APPARATUS

In order to measure the wave forces acting on the horizontal cylinder, experiments were carried out in a small wave channel. The basic wave channel, as shown in Figure 2, consisted of three sections; a deep water section, a shallow water section and a transition section, each fifteen inches wide with a rectangular cross section. The overall channel length was sixty-four feet.

Three quarter inch exterior plywood sheets were used for the channel sides. Vertical rigidity was provided by bracing the plywood sheets with 2 x 4's at various intervals, every four feet in the shallow water section, every foot in the deep water section and every two feet in transition section. Two 2 x 4's were attached to the top of the vertical studs and extended the length of the channel.

Since the bottom of the deep water section was resting on a concrete foundation, only a single section of plywood was used for the channel floor. A double floor was used in the shallow and transition sections. This was done to provide extra strength. The double floor was constructed from two plywood sheets and two and a half inch separators. The sides of these sections were bolted together, through the spacing of the double bottom, with three-eighths threaded rod. Steel angle spacers were placed across the channel top to maintain the width dimension.

Prior to assembly all wooden sections exposed to water were waterproofed. The channel interior was then given two coats of Morewear Vitri-Glaz 1320A. Dow Corning Sealant 780 was applied to all seams and joints.

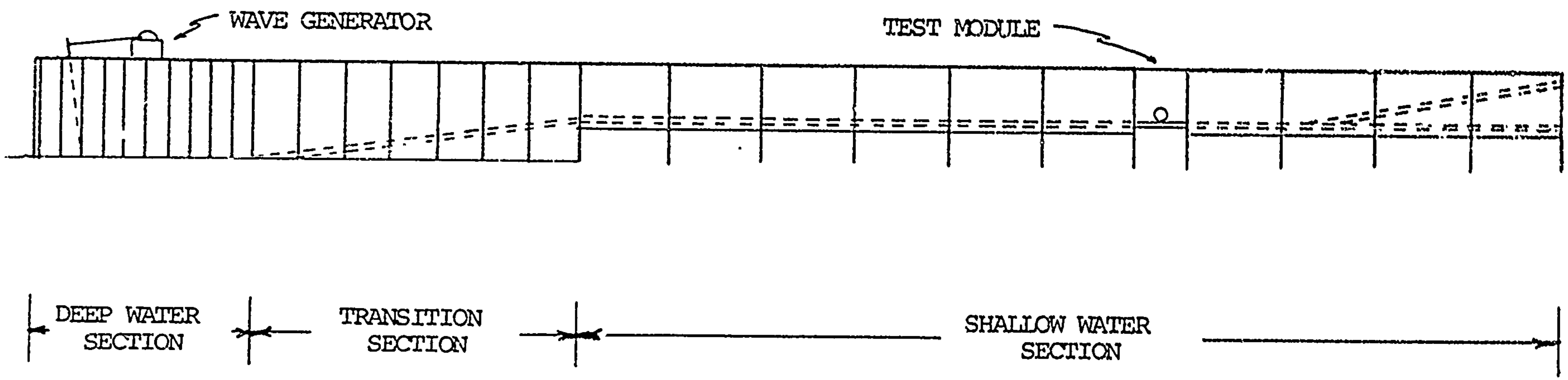


FIGURE 2 WAVE CHANNEL

1. Deep Water Section

Several methods of increasing wave height and steepness are available. One of the most common methods is the generation of waves in a deep water regime and allow them to transition, by shoaling, to a shallow water regime. By the proper choice of depths and shoal slope, the transition can be such that there is no reflection from the shoal, and the resultant shallow water waves are in a near breaking condition. It was this method of increasing wave height that was chosen. As shown in Figure 2, the deep water section was sixteen feet long and four feet deep. A wave generator was located two and three-quarters feet from the closed end of the channel. In order to generate regular waves in the channel a paddle type wave generator was used. An aluminum plate, adequately reinforced, was hinged at the wave channel floor and attached by a pin connection at the top to a driving rod, Figure 3. One-eighth inch teflon sheeting, four inches by fifty-one inches was located along the vertical sides of the plate to prevent leakage from one side to the other. In the space behind the wave paddle the wave motion was damped by use of baffle plates. A two horsepower variable speed drive, with an output speed range of twenty to one hundred and eighty revolutions per minute, was mounted on the top of the wave channel and fitted with a six and three-quarter inch radius face plate. The face plate was provided with ways so that the wave generator driving rod could be adjusted to any eccentricity between zero and eight inches, Figure 4.

2. Transition Section

As previously noted, the wave height was increased by shoaling deep water waves. To accomplish this a 14.14 foot long ramp was constructed and installed between the deep and shallow sections. This

FIGURE 3. WAVE GENERATOR PADDLE

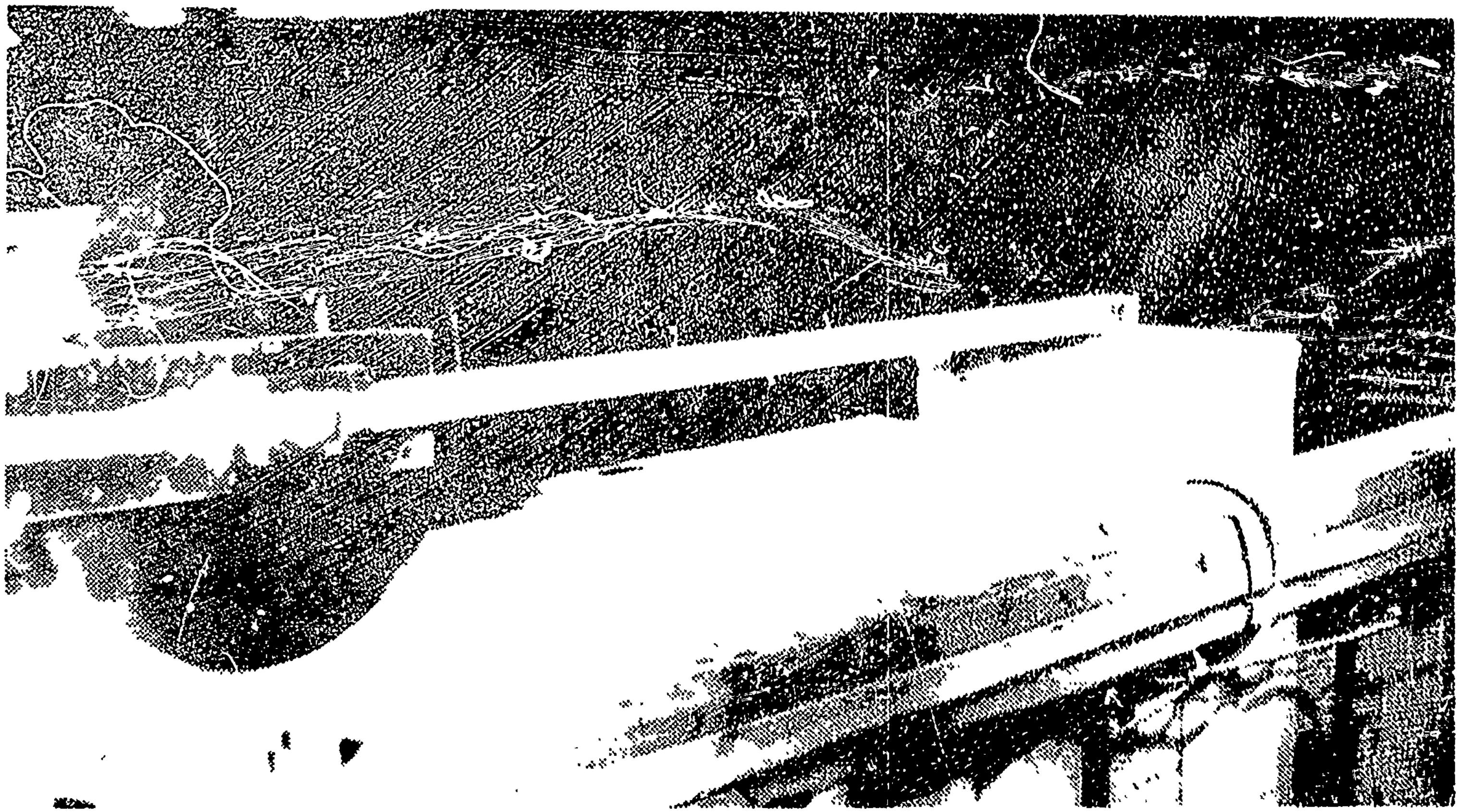


FIGURE 4. WAVE GENERATOR

provided for the transition from deep water to shallow water. In order to reduce the amount of reflection from the transition ramp, the slope was set at 1:6. The change in depth due to the shoal was two feet.

3. Shallow Water Section

The shallow water section had a depth of two feet and a length of forty-two feet. The test module was located twenty four feet from the transition; thus, allowing enough length for the waves to reach a fully developed state following the transition, before reaching the test section. At the end of the channel was located a variable slope beach for purposes of dissipating the wave motion. The beach consisted of metal shavings held between two sheets of perforated metal. These were separated by two inch wooden spacers. A solid sheet of one-eight inch aluminum was attached to the bottom of the beach by three and five-eighths inch separators. On the exposed surface of the beach was attached, parallel to the wave fronts, one by one inch aluminum angles. The maximum slope of the beach was 1:7.

a. Test Module

In order to provide a means of locating the test cylinder and measuring the wave forces acting on it, a separate test module was designed. The test module, consisting of the circular cylinder along with its own walls and floor, was constructed as an integral system in order that it may be removed from the channel. This concept allowed for the maintenance of close tolerances during manufacture and provided for easy access. To accept the test module, the wave channel sides and floor were recessed and made of plexiglass.

The four inch diameter plexiglass cylinder was suspended between the walls of the test module by use of cantilever beams and adjusted to approximately one-sixteenth inch above the floor, Figure 5. It was known *a priori* that this sixteenth of an inch clearance would cause a high velocity jet under the cylinder due to wave action. To prevent this, a flexible plastic barrier was installed in the gap. The barrier was held in place by 'O' ring material pressed into 0.007 inch slot in the cylinder and the test module floor.

In order to suspend the cylinder a small distance off the wave channel floor and at the same time measure forces exerted on it by surface waves, cantilever beam mounts were used as supports as shown in Figures 6 and 7. Bulkheads were fixed in the cylinder at approximately two inches from each end, and the fixed ends of the cantilever beams bolted on these bulkheads. The free ends of the two beams were allowed to protrude slightly beyond the end of the cylinder and into the plexiglass test module walls. The free ends were supported by small self-aligning ball bearings pressed into the plexiglass. Both beams were fitted with strain gages and waterproofed using BLH Barrier 'C', Figure 8. One of the beams with its largest cross sectional dimension horizontal was used to measure the vertical force and the other with its largest cross sectional dimension vertical was used to measure the horizontal force. Calibration tests showed the cross coupling to be negligible.

This design presented some unique problems. The cantilever beams had to be flexible enough to allow measurement of the forces and stiff enough so that the natural frequency was large in comparison to

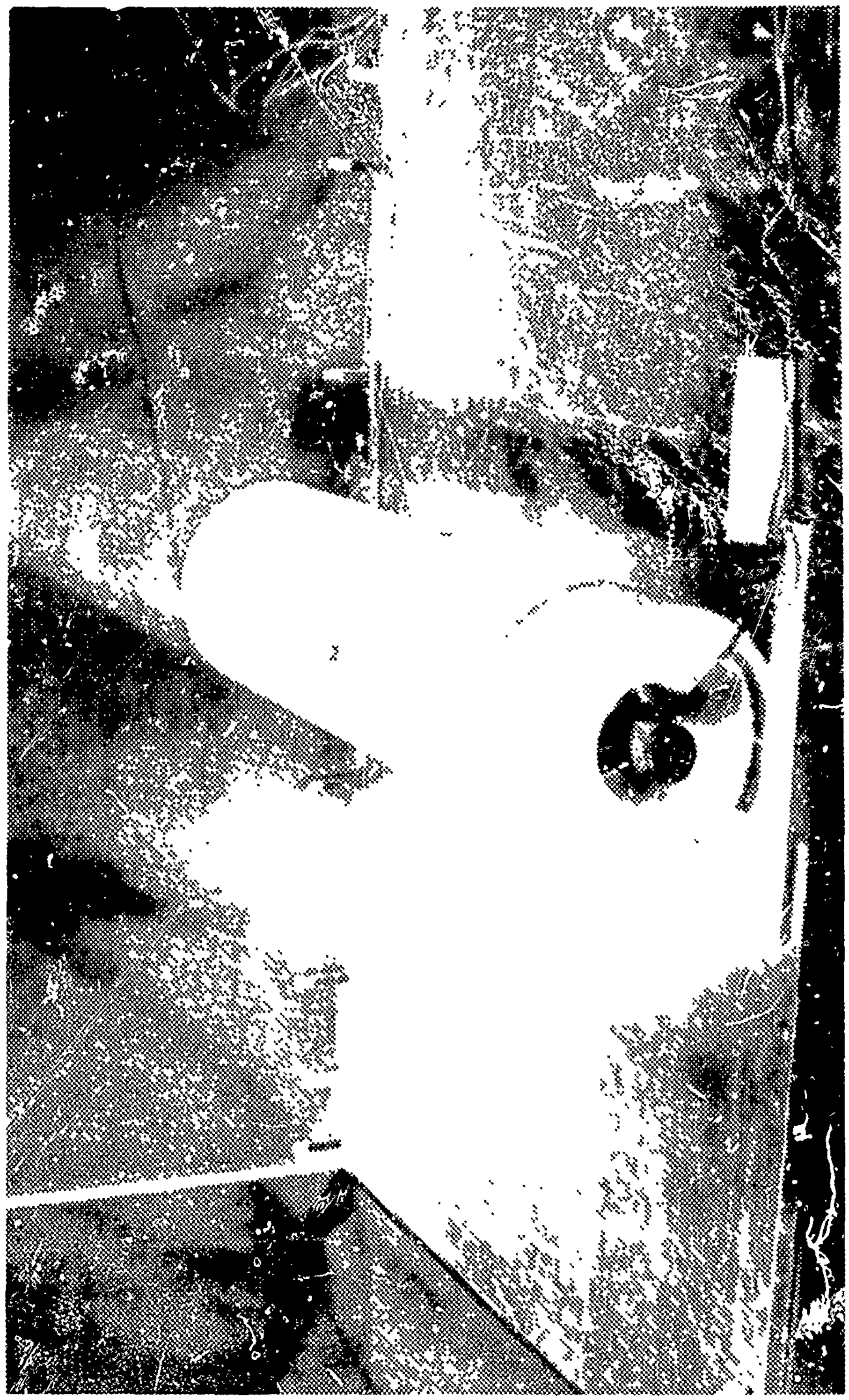


FIGURE 5. TEST MODULE

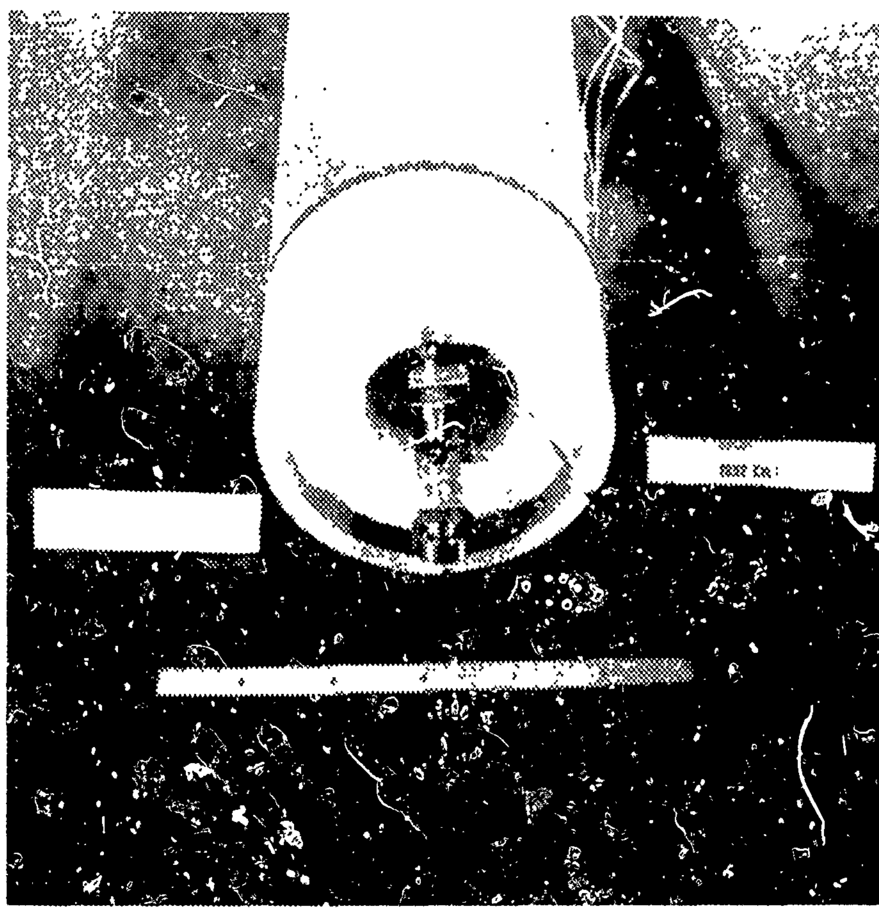


FIGURE 6. HORIZONTAL FORCE CANTILEVER

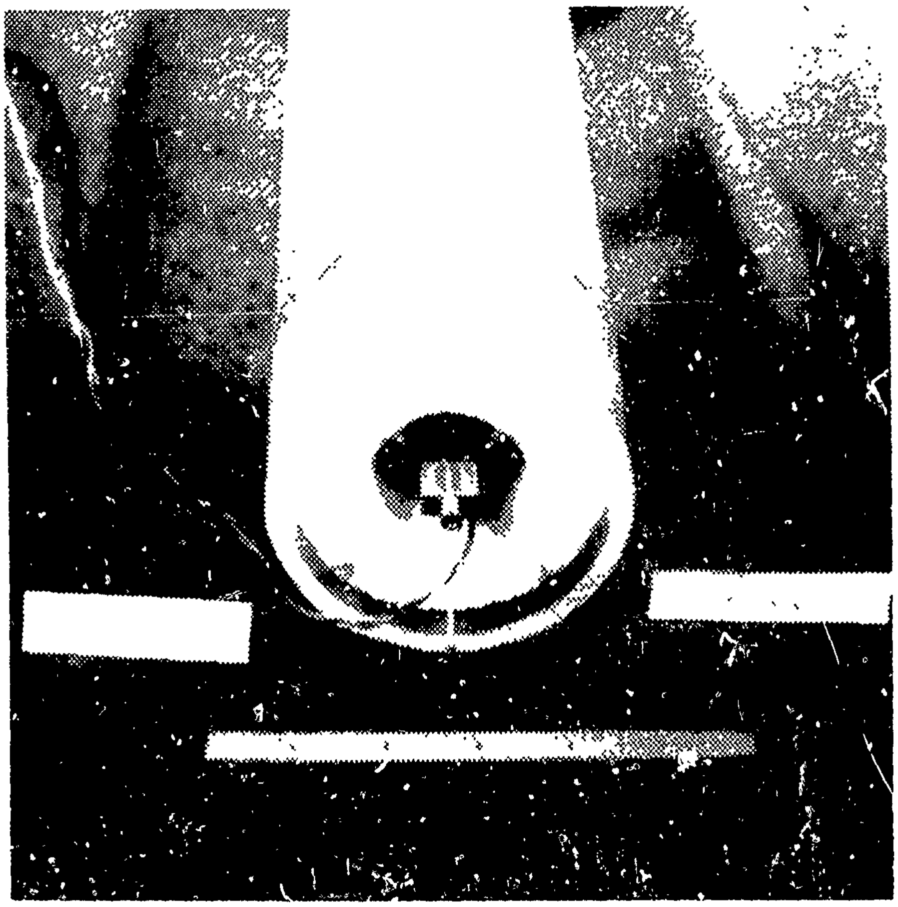
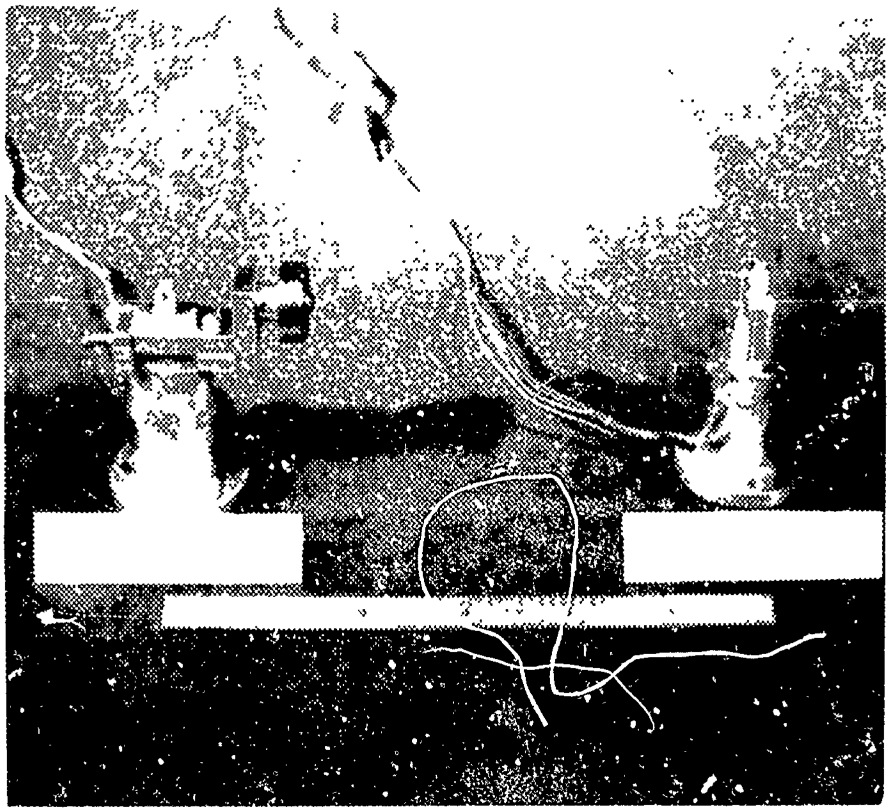


FIGURE [illegible]. VERTICAL [illegible]



[illegible]

the excitation frequency. The characteristics of the strain gage bridge and amplifier determined the minimum strain necessary to produce a measurable output. The strain resulting on a cantilever from a given load is

$$\varepsilon = \frac{6P\ell_b}{Ebh_b^2} \tag{15}$$

where

ε = strain
P = load
ℓ_b = cantilever beam length
E = modulus of elasticity
b = cantilever beam base dimension
h_b = cantilever beam height dimension

The relationship for the spring constant of a cantilever beam is

$$K = \frac{Ebh_b^3}{4\ell_b{}^3} \tag{16}$$

By substituting Equation (15) into (16) a relationship for the spring constant, in terms of the strain and cantilever dimension is determined

$$K = \frac{54\ P^3}{\varepsilon^3 E^2 b^2 h_b^3} \tag{17}$$

It is apparent that the maximum stiffness and, consequently, the maximum natural frequency is obtained by making b, h and ε as small as possible. The minimum value of b was set by the width necessary to mount the strain

gages. The minimum value of ε was determined by the maximum sensitivity of the amplifier/recorder. The maximum stiffness was then achieved by making h as small as possible. However, Equation (15) shows that the beam length decreases with b and h as expressed by

$$\ell_b = \frac{\varepsilon E b h_b^2}{6P} \quad .$$

Thus, the lower limit on h was finally determined by setting a reasonable minimum value for the beam length.

In order to prevent the cylinder from rotating, an offset arm was connected from the horizontal force cantilever to the test module. A Farber bearing, AMS 1K7, was used as a wheel at the test module end of the arm to reduce friction.

4. Wave Height Probe

There are two types of probes in common usage for measuring wave height; these are commonly known as a capacitance and a resistance type probe. The resistance type utilizes two vertical wires placed a small distance apart; the amount of wetting of the wires varies the resistance between them. This active element or "variable resistance" is wired into one leg of a Wheatstone bridge and the signal read out on an amplifier/recorder. Experience has shown, however, that the resistance type probe is extremely sensitive and well suited to measuring small amplitude waves but is rather nonlinear at larger amplitudes.

The capacitance type wave height probe, although less sensitive, tends to be linear over large wave amplitudes and was, therefore, used as the primary method of sensing wave height in the present study. The

probe consists essentially of a single insulated wire which acts as a variable capacitor; the wire acts as one plate and the water the second plate. As the water surface rises and falls, the capacitance varies accordingly.

The probe used in the present study is shown in Figure 9. Located at the bottom of the foil-like support member was a three-eighths inch diameter acrylic rod. The sensing wire was terminated at the bottom in the acrylic rod and at the top at a nylon block. The tip of the acrylic rod was made removable in order to facilitate changing the sensing wire.

A number of wire types were considered and tested prior to selecting number 30 A.W.G. wire with polythermaleze insulation. This wire provided the capability of measuring wave heights to less than one thirty-second of an inch with good accuracy.

The electronic circuit utilized with this probe was obtained in schematic form from Hewlett Packard and is shown in Figure 10. A Hewlett Packard carrier amplifier 350 was used with the probe circuit.

B. TEST PROCEDURE

With the channel filled to the desired level, the test section and wave height probe were set in place. In each instance the probe was immersed to a depth of nine inches. The amplifiers were then adjusted to balance the bridge.

With the use of a transverse mechanism the calibration of the wave probe was accomplished. The probe immersion was varied over a seven inch range in half-inch increments. The gage output was measured both on the Hewlett Packard recorder and one channel of a Brush recorder. This provided the initial calibration information. Prior to and after each set of runs the calibration was checked at several points.

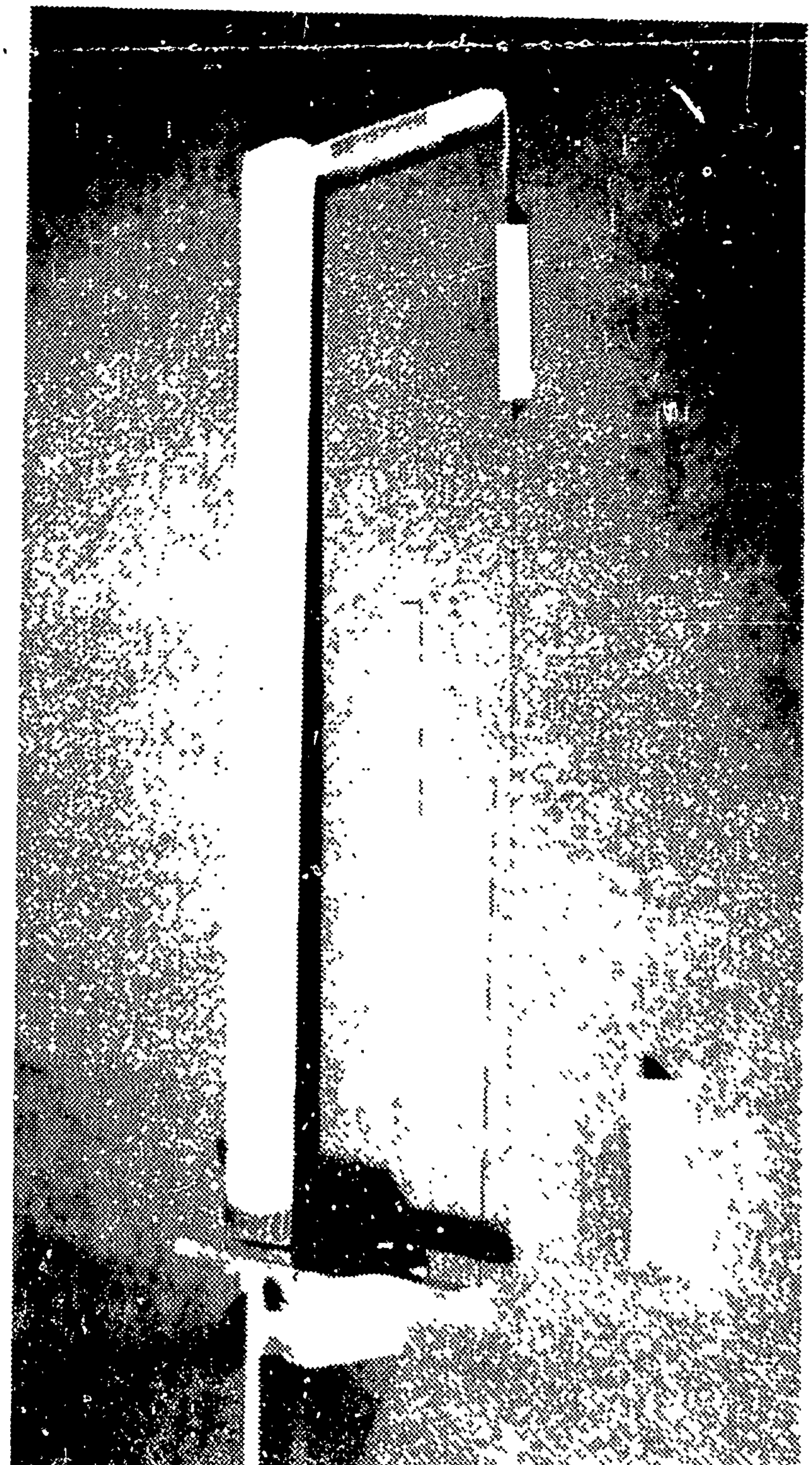
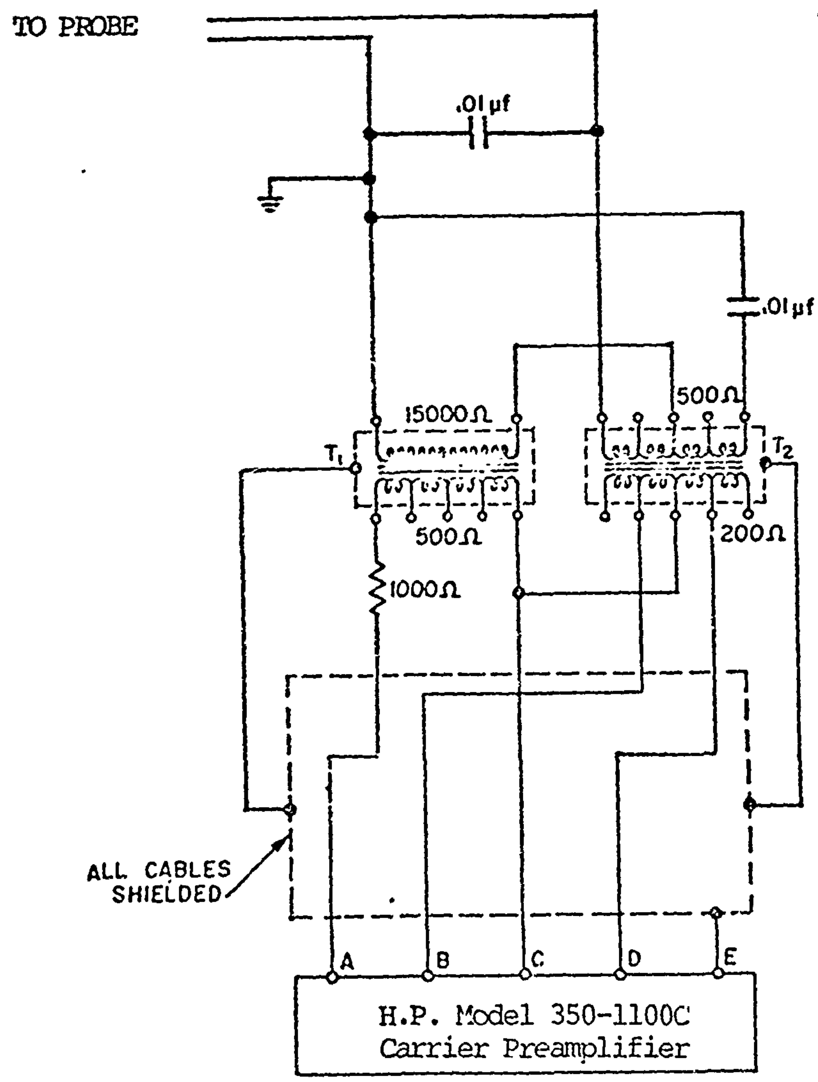


FIGURE 9. WAVE HEIGHT PROBE



T_1: LINE-PLATE TRANSFORMER (UTC O-7)

T_2: LINE-PLATE TRANSFORMER (UTC O-12)

FIGURE 10. WAVE HEIGHT CIRCUIT SCHEMATIC

The force cantilevers were calibrated by exerting a load on the cylinder by means of a series of weights and a wire pully arrangement as shown in Figure 11. The force was transmitted to the cylinder through a series of tapped holes located around the circumference at three, nine and twelve o'clock. Calibration information was obtained from the Bush recorder output by loading the cylinder in half-pound increments. As with the wave height probe, calibration was checked prior to and after each series of runs.

With the calibration completed, the wave generator speed was adjusted for the desired wave length. The wave height probe was located an integer number of wave lengths from the cylinder. Its output was connected to the horizontal grid of an oscilloscope. A second probe was then located directly over the cylinder and its output connected to the vertical oscilloscope grid. By observing the scope pattern the first probe could be adjusted to be in phase with the waves at the cylinder. The second probe was then removed and a data run commenced. During each run the wave generator drive eccentricity was varied from a half-inch to eight inches, or to a point where the waves broke in the channel.

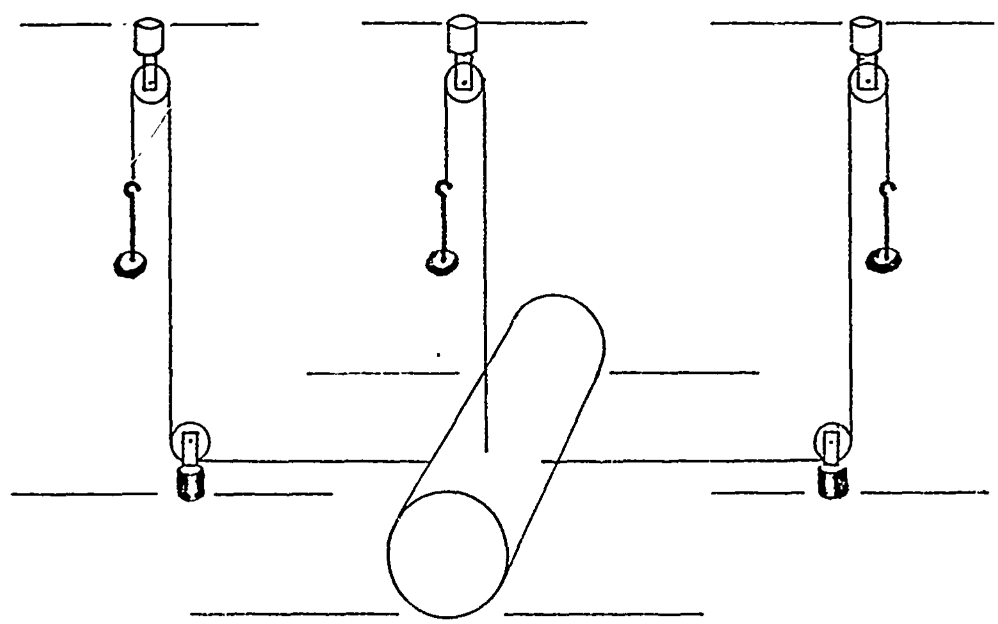


FIGURE 11. CANTILEVER CALIBRATION ARRANGEMENT

IV. PRESENTATION OF RESULTS AND CONCLUSIONS

A. EXPERIMENTAL RESULTS

As discussed in Theoretical Analysis, non-dimensional wave forces can be represented as functions of relative water depth (h/a), relative wave length ($2\pi a/L$) or period parameter (h/gT^2) and relative height parameter (H/2a). In order to ascertain the effect of varying these parameters on the horizontal and vertical components of wave force a test program was established which, for a given run, held water depth and period constant while varying the wave height. Four series of runs were conducted at different water depths corresponding to the relative water depths (h/a) of 9.0, 7.0, 5.5 and 4.0. For each of these water depths, the relative wave length ($2\pi a/L$) was varied over a range from 0.06 to 0.48.

Due to the difficulty in presenting all the wave force traces, a series of representative traces is shown in Figures 12, 13, 14 and 15. These traces represent three wave lengths from the three deeper water depths (h/a = 9.0, 7.0 and 5.5) and two wave lengths for the shallowest water depth (h/a = 4.0). For each of the eleven runs, four wave heights arranged in increasing order are shown. The uppermost trace represents wave height, the middle vertical force and the bottom trace is horizontal force.

The wave height traces show that the waves were generally sinusoidal in nature. This was especially true at the shorter wave lengths. At the greater wave lengths the wave trace departed from the sinusoidal form as the wave height was increased. As can be seen in Figure 12, for the greater lengths, as the height was increased the wave was characterized by sharp peaks and long flat troughs.

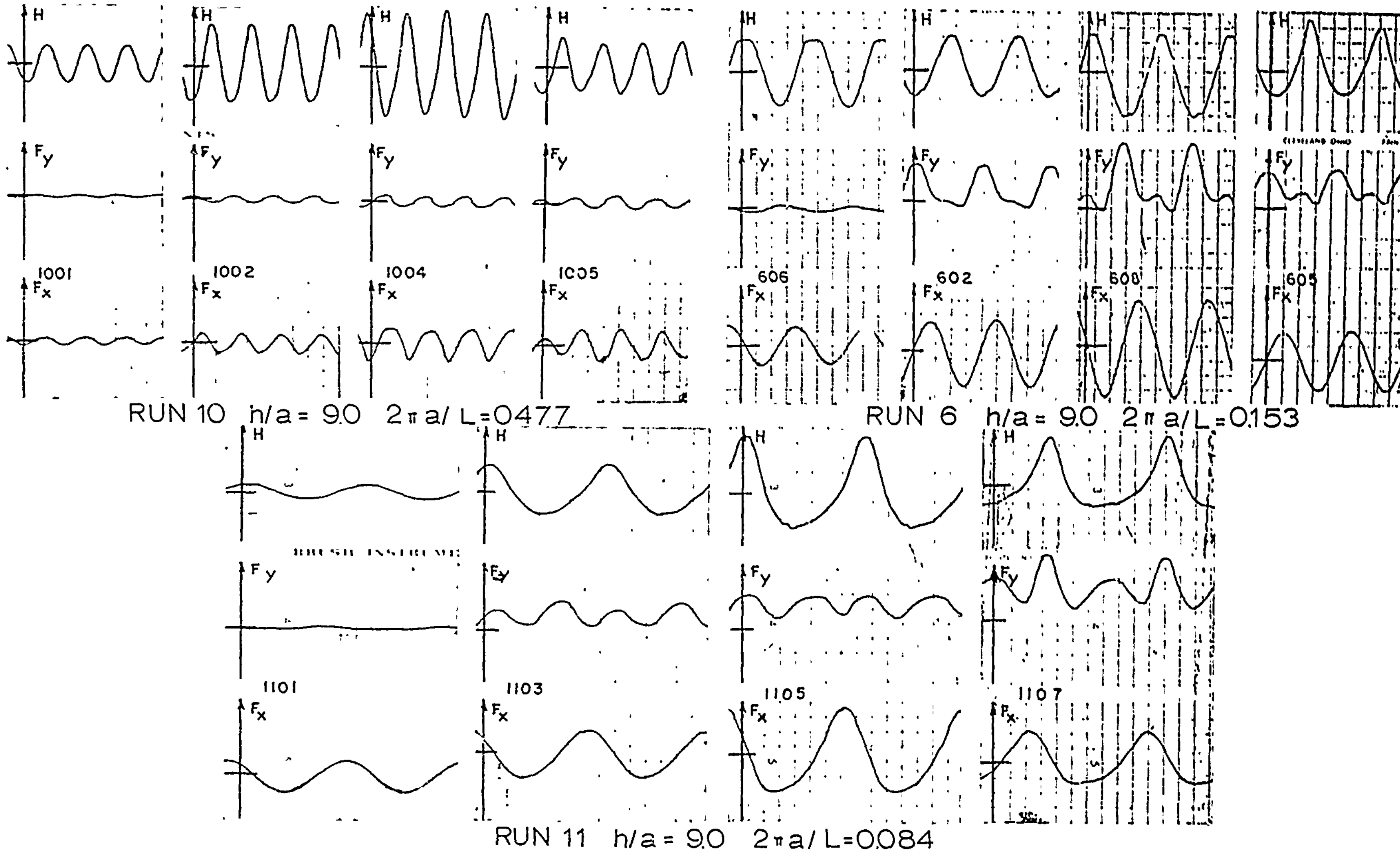


FIGURE 12. WAVE HEIGHT-FORCE TRACES h/a = 9.0

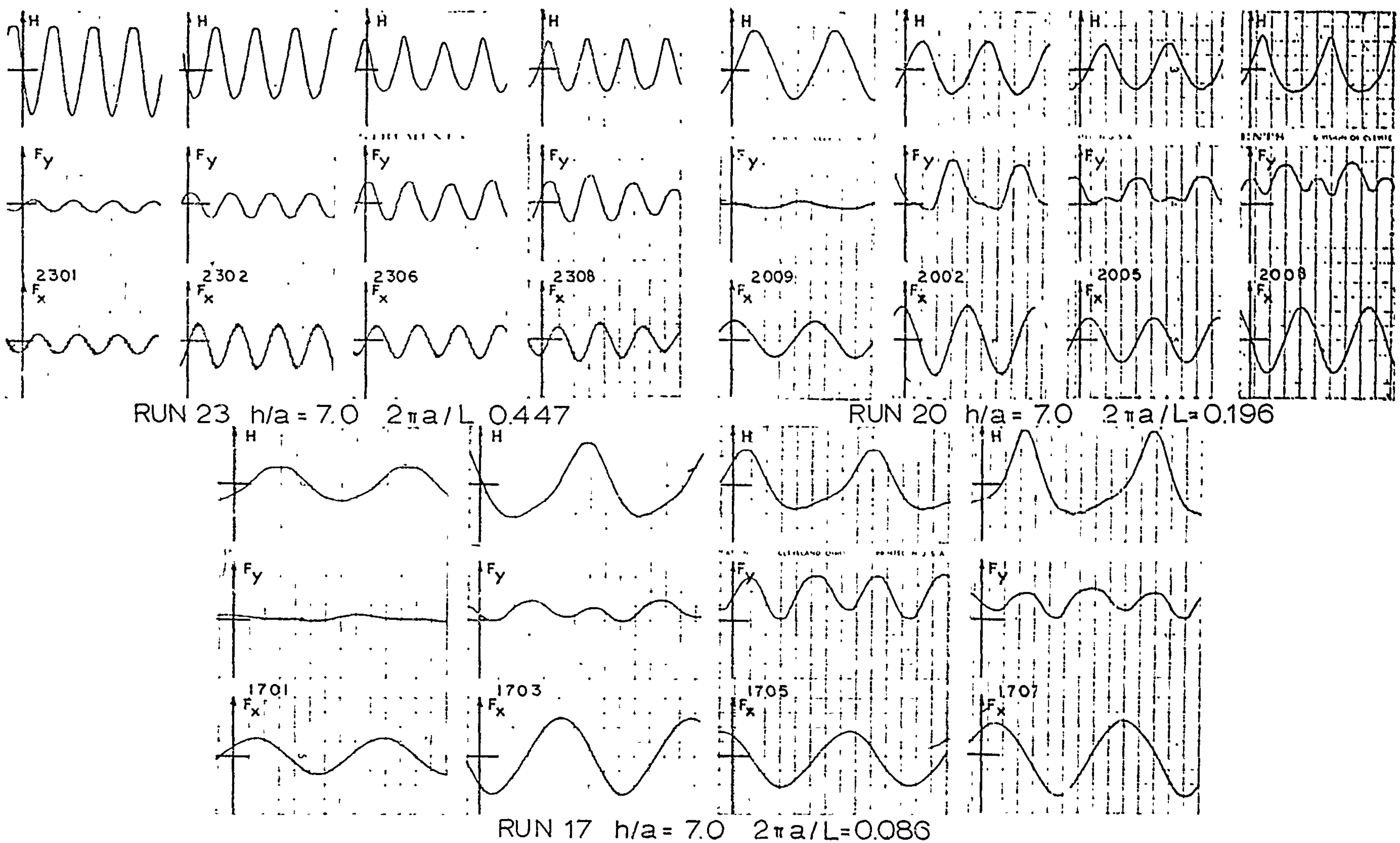


FIGURE 13. WAVE HEIGHT-FORCE TRACES h/a = 7.0

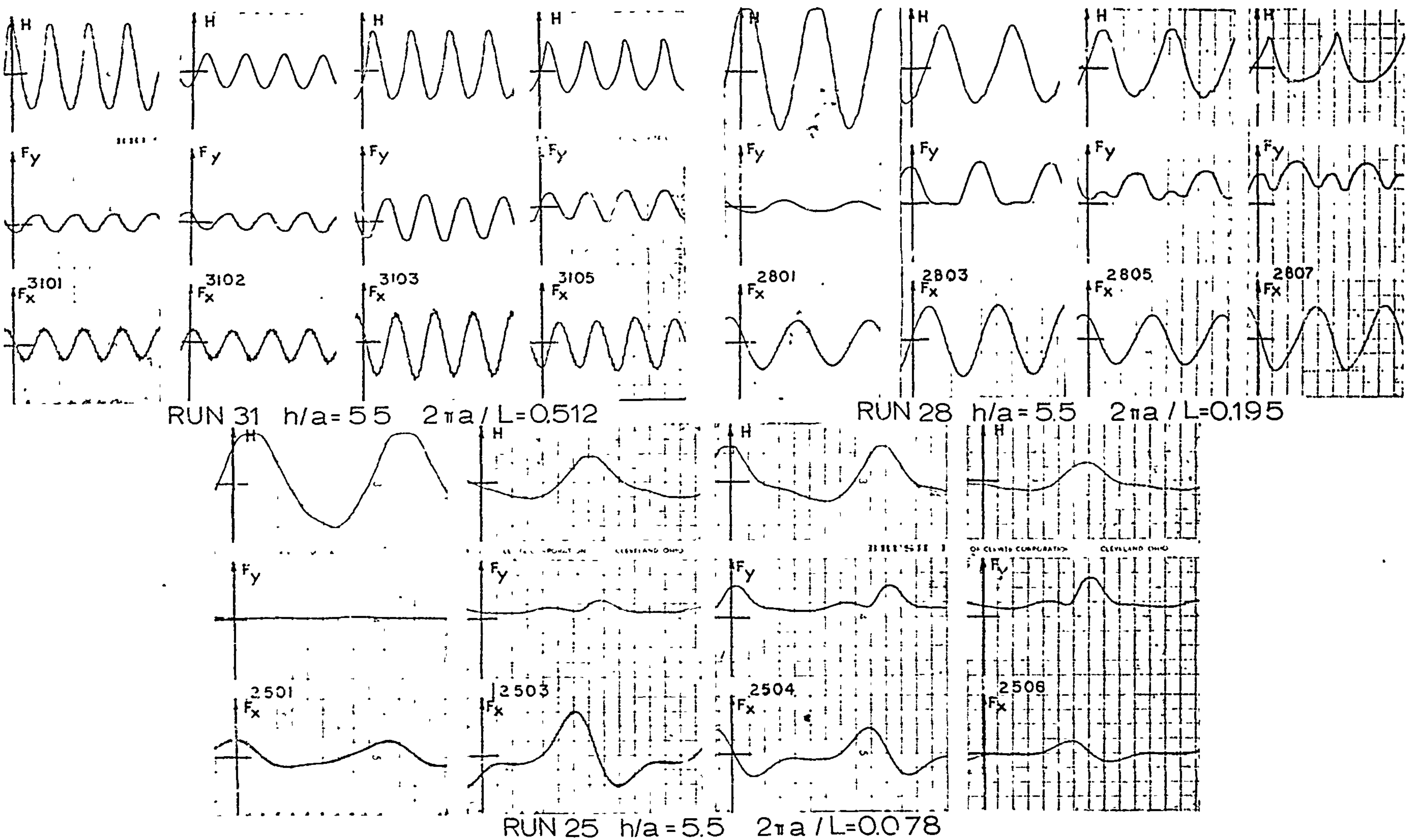


FIGURE 14. WAVE HEIGHT-FORCE TRACES h/a = 5.5

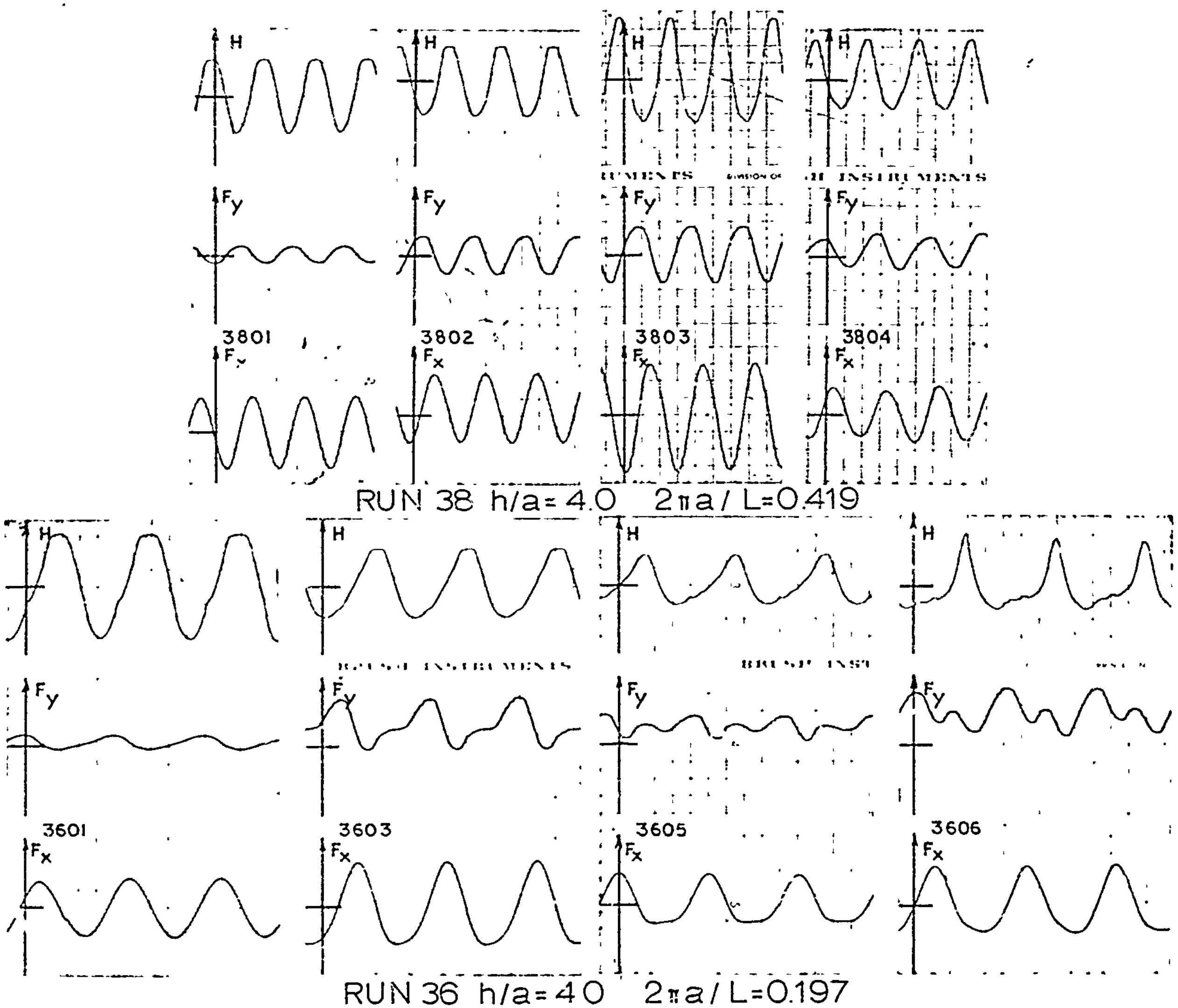


FIGURE 15. WAVE HEIGHT-FORCE TRACES h/a = 4.0

Before discussing the wave force traces a brief discussion of the mechanism involved in the wave forces is in order. In Bernoulli's equation two contributions to the pressure acting on the surface of the cylinder are recognized, an unsteady contribution associated with the time derivative of the potential to the first power (vertical forces) and a term associated with the fluid velocity squared. The velocity squared term tends to be symmetric about the y axis and, consequently, contributes little to the horizontal force. The inertia term is therefore dominant, in the horizontal forces, and increases linearly with wave height H/2a. Examination of the representative traces shows that the horizontal force varied nearly sinusoidally with wave height for all cases except when the wave length became very large. In the case of very long waves, the horizontal force peaks are separated by a null region which corresponded to the wave trough. The maximum value of the horizontal force coincided with the maximum water particle acceleration associated with the incident wave, Equation (9).

For the vertical forces, there are two regimes, one in which the inertial forces dominate and a second in which the velocity squared term dominates. The inertial contribution to the pressure produces both positive and negative values of vertical force. This term tends to be linear in wave height H/2a and have a maximum value of uplift when the cylinder is under the wave trough. The velocity squared term produces only upward forces due to the non-symmetrical flow about the cylinder. This component of vertical force is a function of the wave height squared $(H/2a)^2$ and peaks occur at the points of maximum wave induced velocity occurring at both crest and trough of the wave. Examination of the vertical force traces shows that for the longer waves the force was regular and had a

frequency twice that of the incident wave. The double frequency was caused by the velocity maximums at the crests and troughs. The maximum occurring under the wave crest in the longest waves was apparently attributable to the fact that the velocity under the crest of a shallow water wave is greater than at the trough. Here the upward force was lift dominated. At intermediate wave lengths the reverse occurred. As the wave length was shortened the inertial effects gradually took effect and the maximum occurred at the trough where the two components were additive. Finally, at very short wave lengths the inertial force became dominant and the traces showed a sinusoidal behavior; the lift force associated with the velocity squared term in Bernoulli's equation became negligible.

1. Horizontal Forces

As noted previously, the horizontal force was nearly sinusoidal for the entire series of data runs. It is therefore possible to characterize the force by the maximum value. In order to examine the variation in the horizontal force with varying wave height, plots were constructed of the non-dimensional force coefficient fx ($fx = F_{x\ max}/\rho g a^2 \ell$) versus the relative wave height H/2a. These wave force versus wave height plots are presented in Appendix B. It is apparent from the plots that horizontal force coefficient is characterized by a linear variation with wave height. Inasmuch as the variation of the force coefficient was linear with H/2a, for a given wave length, it is possible to characterize the horizontal force by the dimensionless parameter fx/(H/2a), the slope of the wave force-height plots.

The parameter, $F_{x\ max}/[\rho g a^2 (H/2a)]$ is presented as a function of the relative wave length ($2\pi a/L$) in Figure 16. This figure also presents the result predicted by Morrison's analysis, Equation (12). For the larger

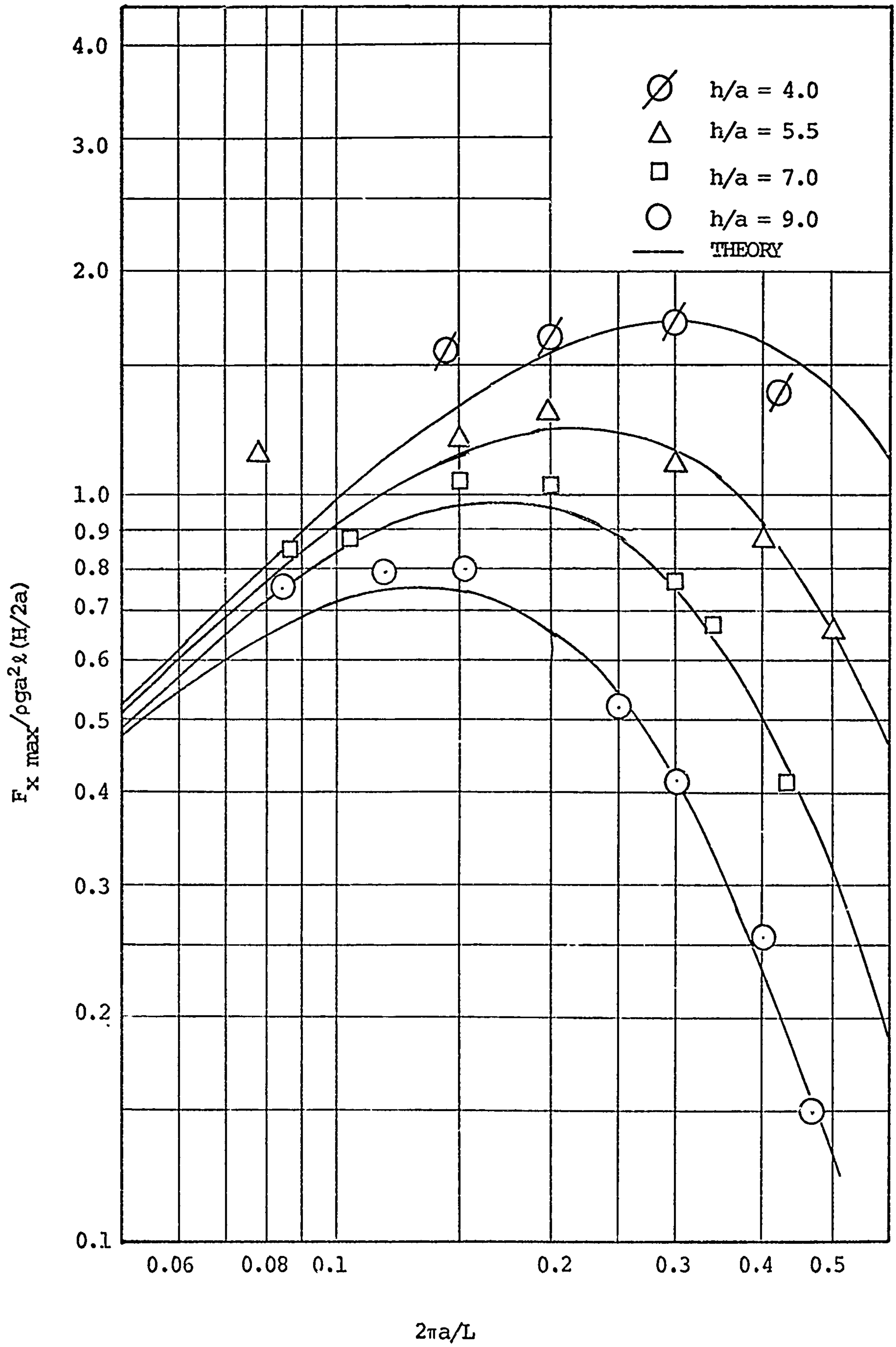


FIGURE 16. HORIZONTAL FORCE COEFFICIENT

values of relative wave length ($2\pi a/L$) the experimental results and theory are in good agreement. This is generally as expected because for the larger values of $2\pi a/L$ the waves are well represented by linear theory and the effect of the free surface is reduced due to the greater water depth. It may be recalled that these were the assumptions upon which the Morrison equation is based. However, for smaller values of $2\pi a/L$, the experimental results are consistently high. This is not unexpected as the waves have become shallow water waves and are not well represented by the linear wave theory. Also, in the case of the smaller depths the effect of the free surface becomes important.

2. Vertical Forces

As previously discussed, the vertical force may display two regimes, one inertia dominated and one dominated by the force associated with the velocity squared term in Bernoulli's equation. The assumption having been made in Equation (13) that the inertia forces would be negligible, the vertical forces would be a function of the velocity squared only and hence a function of $(H/2a)^2$. It is difficult to characterize the force variations with wave height by a single term as two types of flow exist. However, having made the assumption that the force was a function of velocity squared, it was decided to use $fy/(H/2a)^2$ as the characteristic quantity.

Values of $F_{y\ max}/\rho g a^2 \ell (H/2a)^2$ were plotted against the relative wave length ($2\pi a/L$) and presented in Figure 17. The values of this coefficient predicted by a lift force only are also shown in this figure. The agreement between the theory and experimental results appears to be good for the greater water depth ($h/a = 9.0$). However, as the water depth was decreased the agreement became poorer and the experimental data displayed

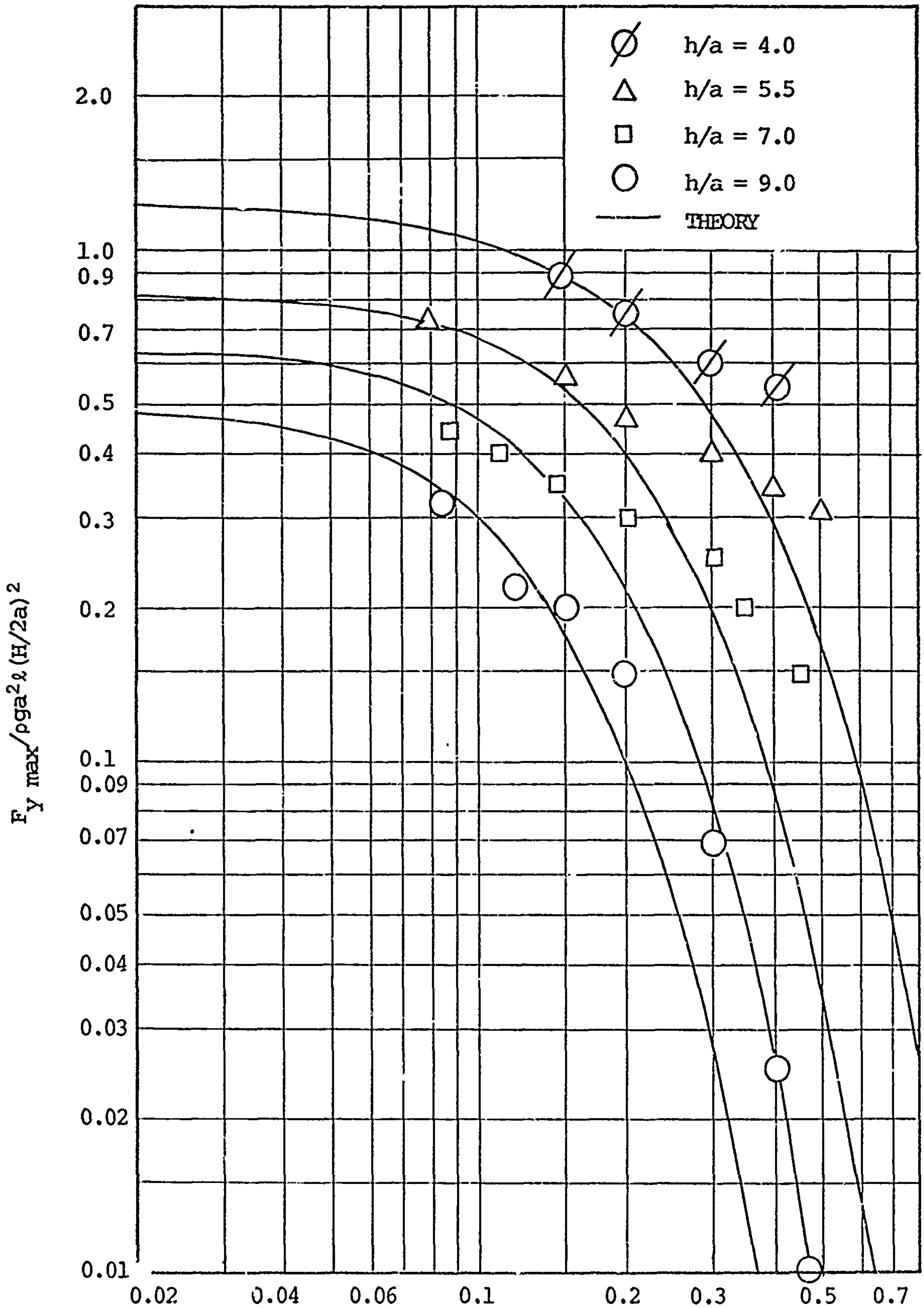


FIGURE 17. VERTICAL FORCE COEFFICIENT

higher force values than predicted by Equation (14); apparently owing to the effect of the free surface and the non-linear effects of the incident wave. Also, as the wave length decreased, or the parameter $2\pi a/L$ increased, it may be noted that the agreement is poor. This is apparently due to the fact that the inertia component becomes dominant and this contribution to the force was neglected in Equation (13).

As waves are often characterized by period rather than wave length, Figure 18 presents the force coefficient as functions of a relative period (h/gT^2).

B. CONCLUSIONS

From the experimental results the following conclusions are considered warranted:

1. The horizontal forces on the cylinder, resulting from the incident gravity waves, increased linearly with wave height.

2. The vertical force showed two regimes, one inertial dominated and one velocity squared dominated. The inertial force regime occurred at shorter wave lengths, while the velocity squared term predominated at the longer wave lengths.

3. The maximum vertical force was always smaller than the maximum horizontal force and the downward vertical force was nearly zero.

4. For greater water depths the theoretical predictions appeared to give valid results for both horizontal and vertical forces in the short wave length range.

5. Horizontal forces became independent of the parameter, $2\pi a/L$, for greater wave lengths.

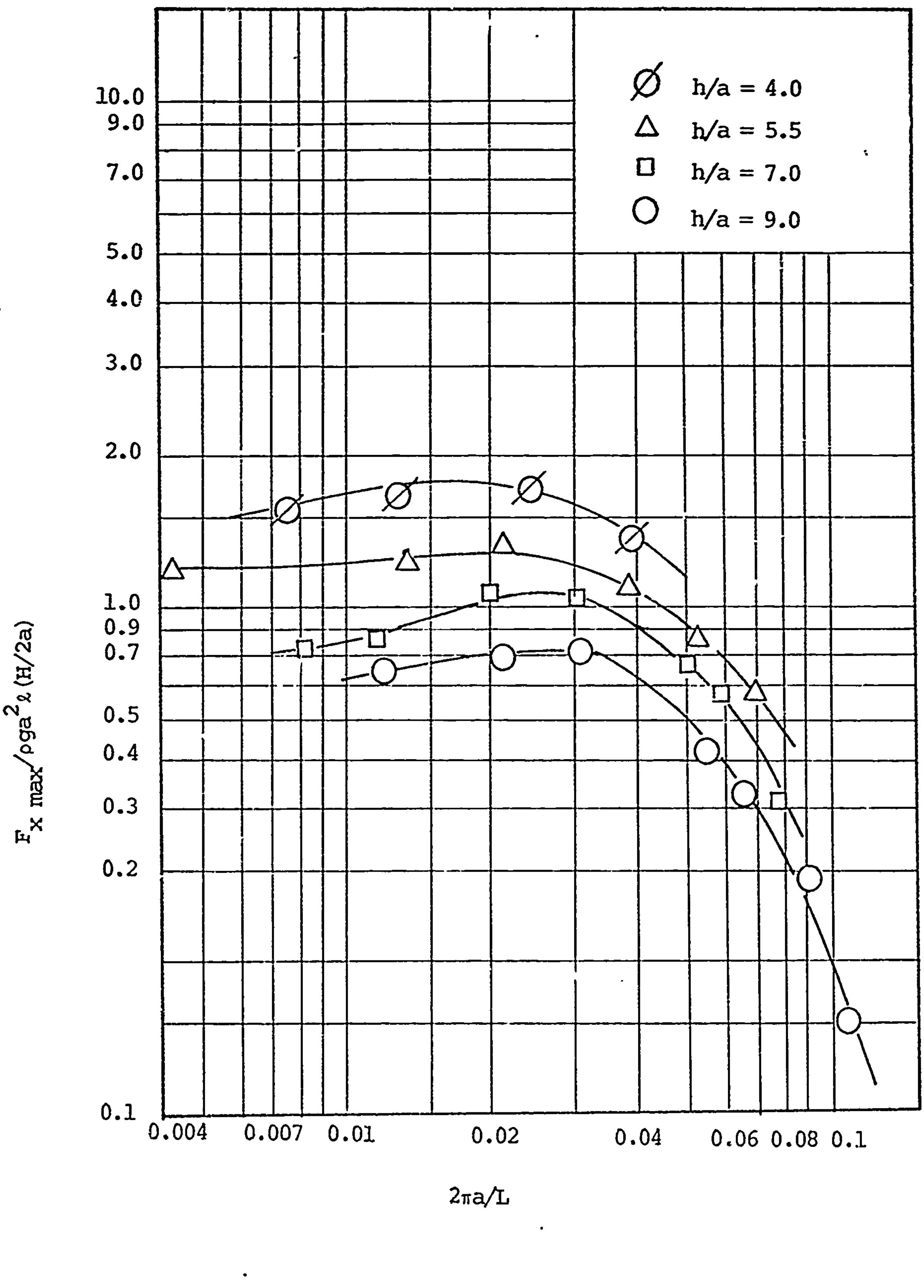


FIGURE 18. HORIZONTAL FORCE COEFFICIENT VERSUS PERIOD PARAMETER

DATA FOR RUN NUMBER 5. TOTAL NUMBER OF RUNS IS 24.

WAVE PERIOD IS 1.482 SECONDS. WAVE LENGTH IS 8.86 FEET. WATER DEPTH IS 18.0 INCHES.

DIMENSICNLESS PARAMETERS ARE 2PIA/GT**2 = 0.1778
2PIA/L = 0.1182
H/L = 0.1693
H/GT**2 = 0.0212

SEGMENT NUMBER	WAVE HEIGHT	FORCE (X)	FORCE (Y)(+)	FORCE (Y)(-)	H/2A	F. COEF (X)	F. COEF (Y)(+)	F. COEF (Y)(-)
501	2.14	0.94	0.38	0.0	0.53	0.44	0.17	0.0
502	3.43	1.55	0.57	0.0	0.86	0.72	0.26	0.0
503	4.88	2.09	0.66	0.0	1.22	0.97	0.30	0.0
504	5.80	2.57	0.81	0.0	1.45	1.19	0.37	0.0
505	7.62	2.84	1.42	0.0	1.90	1.31	0.66	0.0
506	0.61	0.27	0.06	0.0	0.15	0.13	0.03	0.0
507	1.42	0.68	0.15	0.0	0.35	0.31	0.07	0.0
510	4.96	2.07	0.75	0.0	1.24	0.96	0.35	0.0
511	6.25	2.45	1.27	0.0	1.56	1.13	0.59	0.0
512	8.39	3.00	1.80	0.0	2.10	1.39	0.83	0.0

DATA FOR RUN NUMBER 6. TOTAL NUMBER OF RUNS IS 24.

WAVE PERIOD IS 1.233 SECONDS. WAVE LENGTH IS 6.85 FEET. WATER DEPTH IS 18.0 INCHES.

DIMENSICNLESS PARAMETERS ARE 2PIA/GT**2 = 0.2569
2PIA/L = 0.1528
H/L = 0.2189
H/GT**2 = 0.0307

SEGMENT NUMBER	WAVE HEIGHT	FORCE (X)	FORCE (Y)(+)	FORCE (Y)(-)	H/2A	F. COEF (X)	F. COEF (Y)(+)	F. COEF (Y)(-)
601	1.45	0.74	0.15	0.0	0.36	0.34	0.07	0.0
602	3.50	1.54	0.47	0.0	0.88	0.71	0.22	0.0
603	5.87	2.32	0.97	0.0	1.47	1.07	0.45	0.0
604	6.65	2.83	1.50	0.0	1.66	1.31	0.69	0.0
605	7.63	3.00	1.88	0.0	1.91	1.38	0.87	0.0
606	0.69	0.35	0.03	0.0	0.17	0.16	0.01	0.0
607	2.63	1.09	0.27	0.03	0.66	0.50	0.12	0.01
608	4.35	1.96	0.69	0.0	1.09	0.91	0.32	0.0

DATA FOR RUN NUMBER 7. TOTAL NUMBER OF RUNS IS 24.

WAVE PERIOD IS 0.914 SECONDS. WAVE LENGTH IS 4.19 FEET. WATER DEPTH IS 18.0 INCHES.

DIMENSIONLESS PARAMETERS ARE 2PIA/GT**2 = 0.4675
2PIA/L = 0.2502
H/L = 0.3584
H/GT**2 = 0.0558

SEGMENT NUMBER	WAVE HEIGHT	FORCE (X)	FORCE (Y)(+)	FORCE (Y)(-)	H/2A	F. COEF (X)	F. COEF (Y)(+)	F. COEF (Y)(-)
701	1.95	0.49	0.10	0.10	0.49	0.22	0.05	0.05
702	3.76	0.97	0.38	0.15	0.94	0.45	0.17	0.07
703	5.19	1.35	0.64	0.16	1.30	0.62	0.30	0.08
704	5.87	1.62	0.87	0.18	1.47	0.75	0.40	0.08
705	4.12	1.18	0.39	0.12	1.03	0.55	0.18	0.06
706	2.90	0.84	0.42	0.21	0.72	0.39	0.19	0.10

DATA FOR RUN NUMBER 8. TOTAL NUMBER OF RUNS IS 24.

WAVE PERIOD IS 0.829 SECONDS. WAVE LENGTH IS 3.49 FEET. WATER DEPTH IS 18.0 INCHES.

DIMENSIONLESS PARAMETERS ARE 2PIA/GT**2 = 0.5683
2PIA/L = 0.3002
H/L = 0.4300
H/GT**2 = 0.0678

SEGMENT NUMBER	WAVE HEIGHT	FORCE (X)	FORCE (Y)(+)	FORCE (Y)(-)	H/2A	F. COEF (X)	F. COEF (Y)(+)	F. COEF (Y)(-)
801	1.08	0.24	0.03	0.03	0.27	0.11	0.01	0.01
802	2.25	0.50	0.13	0.06	0.56	0.23	0.06	0.03
803	3.20	0.82	0.18	0.15	0.80	0.38	0.08	0.07
804	4.35	1.09	0.30	0.15	1.09	0.50	0.14	0.07
805	5.34	1.33	0.33	0.24	1.33	0.62	0.15	0.11
806	5.57	1.36	0.36	0.24	1.39	0.63	0.17	0.11

DATA FOR RUN NUMBER 9. TOTAL NUMBER OF RUNS IS 24.

WAVE PERIOD IS 0.714 SECONDS. WAVE LENGTH IS 2.61 FEET. WATER DEPTH IS 18.0 INCHES.

DIMENSIONLESS PARAMETERS ARE 2PIA/GT**2 = 0.7661
2PIA/L = 0.4016
H/L = 0.5753
H/GT**2 = 0.0914

SEGMENT NUMBER	WAVE HEIGHT	FORCE (X)	FORCE (Y)(+)	FORCE (Y)(-)	H/2A	F. COEF (X)	F. COEF (Y)(+)	F. COEF (Y)(-)
901	0.93	0.12	0.04	0.01	0.23	0.06	0.02	0.01
902	2.02	0.27	0.06	0.06	0.50	0.12	0.03	0.03
903	2.94	0.49	0.10	0.07	0.73	0.22	0.05	0.03
904	3.28	0.59	0.15	0.08	0.82	0.27	0.07	0.04

DATA FOR RUN NUMBER 11. TOTAL NUMBER OF RUNS IS 24.

WAVE PERIOD IS 1.961 SECONDS. WAVE LENGTH IS 12.54 FEET. WATER DEPTH IS 18.0 INCHES.

DIMENSIONLESS PARAMETERS ARE 2PIA/GT**2 = 0.1016
2PIA/L = 0.0835
H/L = 0.1196
H/GT**2 = 0.0121

SEGMENT NUMBER	WAVE HEIGHT	FORCE (X)	FORCE (Y)(+)	FORCE (Y)(-)	H/2A	F. COEF (X)	F. COEF (Y)(+)	F. COEF (Y)(-)
1101	0.76	0.28	0.01	0.0	0.19	0.13	0.01	0.0
1102	1.64	0.69	0.13	0.0	0.41	0.32	0.06	0.0
1103	1.90	0.97	0.31	0.0	0.47	0.45	0.15	0.0
1104	3.43	1.35	0.58	0.0	0.86	0.62	0.27	0.0
1105	4.76	1.78	0.91	0.0	1.19	0.82	0.42	0.0
1106	6.02	2.16	0.96	0.0	1.50	1.00	0.44	0.0
1107	7.01	2.16	1.57	0.0	1.75	1.00	0.73	0.0

DATA FOR RUN NUMBER 17. TOTAL NUMBER OF RUNS IS 24.

WAVE PERIOD IS 2.092 SECONDS. WAVE LENGTH IS 12.13 FEET. WATER DEPTH IS 14.0 INCHES.

DIMENSIONLESS PARAMETERS ARE 2PIA/GT**2 = 0.0892
2PIA/L = 0.0864
H/L = 0.0962
H/GT**2 = 0.0083

SEGMENT NUMBER	WAVE HEIGHT	FORCE (X)	FORCE (Y)(+)	FORCE (Y)(-)	H/2A	F. COEF (X)	F. COEF (Y)(+)	F. COEF (Y)(-)
1701	0.78	0.38	0.07	0.0	0.19	0.16	0.03	0.0
1702	1.19	0.54	0.13	0.0	0.30	0.2[illegible]	0.06	0.0
1703	1.72	0.76	0.23	0.0	0.43	0.35	0.11	0.0
1704	2.00	0.87	0.34	0.0	0.50	0.40	0.16	0.0
1705	2.56	1.14	0.44	0.0	0.64	0.53	0.20	0.0
1706	3.00	1.31	0.52	0.0	0.75	0.60	0.24	0.0
1707	3.34	1.42	0.60	0.0	0.83	0.65	0.28	0.0

DATA FOR RUN NUMBER 18. TOTAL NUMBER OF RUNS IS 24.

WAVE PERIOD IS 1.757 SECONDS. WAVE LENGTH IS 9.94 FEET. WATER DEPTH IS 14.0 INCHES.

DIMENSIONLESS PARAMETERS ARE 2PIA/GT**2 = 0.1265
2PIA/L = 0.1054
H/L = 0.1174
H/GT**2 = 0.0117

SEGMENT NUMBER	WAVE HEIGHT	FORCE (X)	FORCE (Y)(+)	FORCE (Y)(-)	H/2A	F. COEF (X)	F. COEF (Y)(+)	F. COEF (Y)(-)
1801	0.45	0.22	0.02	0.0	0.11	0.10	0.01	0.0
1802	1.50	0.70	0.14	0.0	0.38	0.32	0.07	0.0
1803	1.80	0.80	0.20	0.0	0.45	0.37	0.09	0.0
1804	2.23	1.10	0.30	0.0	0.56	0.51	0.14	0.0
1805	2.68	1.50	0.45	0.05	0.67	0.69	0.21	0.02
1806	3.12	1.55	0.50	0.08	0.78	0.72	0.23	0.04
1807	3.60	1.60	0.63	0.95	0.90	0.74	0.29	0.44
1808	3.90	1.90	0.70	0.10	0.97	0.88	0.32	0.05
1809	4.45	2.25	0.72	0.12	1.11	1.04	0.33	0.06
1810	4.73	2.55	0.82	0.15	1.18	1.18	0.38	0.07
1811	4.90	2.75	1.10	0.15	1.22	1.27	0.51	0.07

DATA FOR RUN NUMBER 19. TOTAL NUMBER OF RUNS IS 24.

WAVE PERIOD IS 1.352 SECONDS. WAVE LENGTH IS 7.20 FEET. WATER DEPTH IS 14.0 INCHES.

DIMENSIONLESS PARAMETERS ARE 2PIA/GT**2 = 0.2137
2PIA/L = 0.1454
H/L = 0.1620
H/GT**2 = 0.0198

SEGMENT NUMBER	WAVE HEIGHT	FORCE (X)	FORCE (Y)(+)	FORCE (Y)(-)	H/2A	F. COEF (X)	F. COEF (Y)(+)	F. COEF (Y)(-)
1901	1.28	0.79	0.14	0.04	0.32	0.36	0.07	0.02
1902	1.84	1.14	0.28	0.03	0.46	0.53	0.13	0.01
1903	2.67	1.42	0.45	0.0	0.67	0.65	0.21	0.0
1904	3.09	1.85	0.56	0.0	0.77	0.86	0.26	0.0
1905	3.78	2.18	0.57	0.0	0.94	1.01	0.26	0.0
1906	4.38	2.72	0.75	0.0	1.09	1.26	0.35	0.0
1907	5.13	3.00	0.93	0.0	1.28	1.38	0.43	0.0
1908	5.75	3.13	1.14	0.0	1.44	1.45	0.53	0.0
1909	6.75	3.13	1.14	0.0	1.69	1.45	0.53	0.0
1910	0.48	0.20	0.15	0.15	0.12	0.09	0.07	0.07

DATA FOR RUN NUMBER 20. TOTAL NUMBER OF RUNS IS 24.

WAVE PERIOD IS 1.089 SECONDS. WAVE LENGTH IS 5.34 FEET. WATER DEPTH IS 14.0 INCHES.

DIMENSIONLESS PARAMETERS ARE 2PIA/GT**2 = 0.3293
2PIA/L = 0.1961
H/L = 0.2184
H/GT**2 = 0.0306

SEGMENT NUMBER	WAVE HEIGHT	FORCE (X)	FORCE (Y)(+)	FORCE (Y)(-)	H/2A	F. COEF (X)	F. COEF (Y)(+)	F. COEF (Y)(-)
2001	1.53	0.90	0.18	0.06	0.38	0.42	0.08	0.03
2002	2.31	1.47	0.33	0.06	0.58	0.68	0.15	0.03
2003	3.06	1.63	0.49	0.0	0.76	0.76	0.23	0.0
2004	3.00	1.77	0.48	0.0	0.75	0.82	0.22	0.0
2005	3.81	2.04	0.55	0.0	0.95	0.94	0.26	0.0
2006	4.50	2.32	0.69	0.0	1.13	1.07	0.32	0.0
2007	5.25	2.72	0.78	0.0	1.31	1.26	0.36	0.0
2008	6.17	3.00	0.85	0.0	1.54	1.38	0.39	0.0
2009	0.72	0.35	0.03	0.03	0.18	0.16	0.01	0.01

DATA FOR RUN NUMBER 21. TOTAL NUMBER OF RUNS IS 24.

WAVE PERIOD IS 0.846 SECONDS. WAVE LENGTH IS 3.55 FEET. WATER DEPTH IS 14.0 INCHES.

DIMENSIONLESS PARAMETERS ARE 2PIA/GT**2 = 0.5457
2PIA/L = 0.2950
H/L = 0.3287
H/GT**2 = 0.0507

SEGMENT NUMBER	WAVE HEIGHT	FORCE (X)	FORCE (Y)(+)	FORCE (Y)(-)	H/2A	F. COEF (X)	F. COEF (Y)(+)	F. COEF (Y)(-)
2101	1.73	0.76	0.21	0.09	0.43	0.35	0.10	0.04
2102	2.55	1.14	0.34	0.16	0.64	0.53	0.16	0.08
2103	3.66	2.94	0.48	0.22	0.91	1.36	0.22	0.10
2104	4.49	1.85	0.67	0.23	1.12	0.86	0.31	0.11
2105	4.84	1.98	0.55	0.24	1.21	0.91	0.26	0.11
2107	0.84	0.24	0.06	0.04	0.21	0.11	0.03	0.02

DATA FOR RUN NUMBER 22. TOTAL NUMBER OF RUNS IS 24.

WAVE PERIOD IS 0.780 SECONDS. WAVE LENGTH IS 3.06 FEET. WATER DEPTH IS 14.0 INCHES.

DIMENSIONLESS PARAMETERS ARE 2PIA/GT**2 = 0.6420
2PIA/L = 0.3417
H/L = 0.3807
H/GT**2 = 0.0596

SEGMENT NUMBER	WAVE HEIGHT	FORCE (X)	FORCE (Y)(+)	FORCE (Y)(-)	H/2A	F. COEF (X)	F. COEF (Y)(+)	F. COEF (Y)(-)
2201	2.75	0.93	0.33	0.18	0.69	0.43	0.15	0.08
2203	3.46	1.25	0.45	0.24	0.86	0.58	0.21	0.11
2204	4.38	1.47	0.61	0.30	1.09	0.68	0.28	0.14
2205	4.27	1.63	0.45	0.27	1.07	0.76	0.21	0.12
2206	4.27	1.63	0.40	0.19	1.07	0.76	0.19	0.09
2208	0.82	0.38	0.07	0.06	0.20	0.18	0.03	0.03
2209	1.35	0.46	0.17	0.09	0.34	0.21	0.08	0.04
2210	2.06	0.69	0.25	0.13	0.51	0.32	0.11	0.06

DATA FOR RUN NUMBER 23. TOTAL NUMBER OF RUNS IS 24.

WAVE PERIOD IS 0.678 SECONDS. WAVE LENGTH IS 2.35 FEET. WATER DEPTH IS 14.0 INCHES.

DIMENSIONLESS PARAMETERS ARE 2PIA/GT**2 = 0.8496
2PIA/L = 0.4465
H/L = 0.4975
H/GT**2 = 0.0789

SEGMENT NUMBER	WAVE HEIGHT	FORCE (X)	FORCE (Y)(+)	FORCE (Y)(-)	H/2A	F. COEF (X)	F. COEF (Y)(+)	F. COEF (Y)(-)
2301	1.01	0.22	0.06	0.06	0.25	0.10	0.03	0.03
2302	1.89	0.42	0.16	0.10	0.47	0.19	0.08	0.05
2303	2.86	0.63	0.27	0.16	0.71	0.29	0.12	0.08
2304	3.36	0.65	0.27	0.15	0.84	0.30	0.12	0.07
2305	3.47	0.76	0.33	0.19	0.87	0.35	0.15	0.09
2306	3.51	0.79	0.33	0.21	0.88	0.36	0.15	0.10
2308	3.66	0.90	0.38	0.24	0.91	0.42	0.17	0.11

DATA FOR RUN NUMBER 10. TOTAL NUMBER OF RUNS IS 24.

WAVE PERIOD IS 0.655 SECONDS. WAVE LENGTH IS 2.20 FEET. WATER DEPTH IS 18.0 INCHES.

DIMENSIONLESS PARAMETERS ARE 2PIA/GT**2 = 0.9104
2PIA/L = 0.4768
H/L = 0.6830
H/GT**2 = 0.1087

SEGMENT NUMBER	WAVE HEIGHT	FORCE (X)	FORCE (Y)(+)	FORCE (Y)(-)	H/2A	F. COEF (X)	F. COEF (Y)(+)	F. COEF (Y)(-)
1001	0.99	0.08	0.01	0.01	0.25	0.04	0.01	0.01
1002	2.02	0.19	0.03	0.03	0.50	0.09	0.01	0.01
1003	2.55	0.27	0.04	0.04	0.64	0.12	0.02	0.02
1004	2.75	0.32	0.06	0.06	0.69	0.15	0.03	0.03
1005	2.90	0.38	0.07	0.07	0.72	0.17	0.03	0.03

DATA FOR RUN NUMBER 25. TOTAL NUMBER OF RUNS IS 24.

WAVE PERIOD IS 2.549 SECONDS. WAVE LENGTH IS 13.46 FEET. WATER DEPTH IS 11.0 INCHES.

DIMENSIONLESS PARAMETERS ARE 2PIA/GT**2 = 0.0601
2PIA/L = 0.0778
H/L = 0.0681
H/GT**2 = 0.0044

SEGMENT NUMBER	WAVE HEIGHT	FORCE (X)	FORCE (Y)(+)	FORCE (Y)(-)	H/2A	F. COEF (X)	F. COEF (Y)(+)	F. COEF (Y)(-)
2501	0.51	0.33	0.03	0.0	0.13	0.15	0.01	0.0
2502	0.81	0.53	0.08	0.0	0.20	0.25	0.04	0.0
2503	1.07	0.76	0.18	0.0	0.27	0.35	0.08	0.0
2504	1.41	0.87	0.33	0.0	0.35	0.40	0.15	0.0
2505	1.73	1.20	0.48	0.0	0.43	0.55	0.22	0.0
2506	1.91	1.36	0.52	0.0	0.48	0.63	0.24	0.0
2507	2.14	1.63	0.51	0.0	0.53	0.76	0.24	0.0
2508	2.59	1.84	0.60	0.0	0.65	0.85	0.28	0.0

DATA FOR RUN NUMBER 27. TOTAL NUMBER OF RUNS IS 24.

WAVE PERIOD IS 1.436 SECONDS. WAVE LENGTH IS 7.09 FEET. WATER DEPTH IS 11.0 INCHES.

DIMENSIONLESS PARAMETERS ARE 2PIA/GT**2 = 0.1894
2PIA/L = 0.1477
H/L = 0.1293
H/GT**2 = 0.0138

SEGMENT NUMBER	WAVE HEIGHT	FORCE (X)	FORCE (Y)(+)	FORCE (Y)(-)	H/2A	F. COEF (X)	F. COEF (Y)(+)	F. COEF (Y)(-)
2701	0.55	0.35	0.08	0.0	0.14	0.16	0.04	0.0
2702	1.10	0.79	0.13	0.03	0.27	0.36	0.06	0.01
2703	1.66	1.14	0.28	0.0	0.41	0.53	0.13	0.0
2704	2.14	1.50	0.49	0.0	0.53	0.69	0.23	0.0
2705	2.86	1.91	0.57	0.0	0.71	0.88	0.26	0.0
2706	3.58	2.18	0.66	0.0	0.89	1.01	0.30	0.0
2707	3.81	2.45	0.82	0.0	0.95	1.13	0.38	0.0
2708	5.11	3.00	1.20	0.0	1.28	1.38	0.55	0.0
2709	6.10	3.41	1.65	0.0	1.52	1.57	0.76	0.0

DATA FOR RUN NUMBER 28. TOTAL NUMBER OF RUNS IS 24.

WAVE PERIOD IS 1.150 SECONDS. WAVE LENGTH IS 5.36 FEET. WATER DEPTH IS 11.0 INCHES.

DIMENSIONLESS PARAMETERS ARE 2PIA/GT**2 = 0.2953
2PIA/L = 0.1954
H/L = 0.1710
H/GT**2 = 0.0215

SEGMENT NUMBER	WAVE HEIGHT	FORCE (X)	FORCE (Y)(+)	FORCE (Y)(-)	H/2A	F. COEF (X)	F. COEF (Y)(+)	F. COEF (Y)(-)
2801	0.65	0.46	0.06	0.03	0.16	0.21	0.03	0.01
2802	1.34	0.98	0.21	0.03	0.33	0.45	0.10	0.01
2803	1.98	1.42	0.42	0.0	0.49	0.65	0.19	0.0
2804	2.63	1.98	0.57	0.0	0.66	0.91	0.26	0.0
2805	3.36	2.45	0.66	0.0	0.84	1.13	0.30	0.0
2806	4.08	2.79	0.72	0.0	1.02	1.29	0.33	0.0
2807	5.03	3.13	0.84	0.0	1.26	1.45	0.39	0.0
2808	5.79	3.41	0.96	0.0	1.45	1.57	0.44	0.0

DATA FOR RUN NUMBER 29. TOTAL NUMBER OF RUNS IS 24.

WAVE PERIOD IS 0.854 SECONDS. WAVE LENGTH IS 3.47 FEET. WATER DEPTH IS 11.0 INCHES.

DIMENSIONLESS PARAMETERS ARE 2PIA/GT**2 = 0.5355
2PIA/L = 0.3015
H/L = 0.2639
H/GT**2 = 0.0391

SEGMENT NUMBER	WAVE HEIGHT	FORCE (X)	FORCE (Y)(+)	FORCE (Y)(-)	H/2A	F. COEF (X)	F. COEF (Y)(+)	F. COEF (Y)(-)
2901	0.76	0.44	0.12	0.07	0.19	0.20	0.06	0.03
2902	1.68	1.04	0.30	0.15	0.42	0.48	0.14	0.07
2903	2.52	1.42	0.51	0.21	0.63	0.65	0.24	0.10
2904	3.51	1.98	0.60	0.24	0.88	0.91	0.28	0.11
2905	4.04	2.45	0.75	0.22	1.01	1.13	0.35	0.10
2906	4.58	2.72	1.05	0.30	1.14	1.26	0.49	0.14

DATA FOR RUN NUMBER 30. TOTAL NUMBER OF RUNS IS 24.

WAVE PERIOD IS 0.727 SECONDS. WAVE LENGTH IS 2.64 FEET. WATER DEPTH IS 11.0 INCHES.

DIMENSIONLESS PARAMETERS ARE 2PIA/GT**2 = 0.7390
2PIA/L = 0.3968
H/L = 0.3474
H/GT**2 = 0.0539

SEGMENT NUMBER	WAVE HEIGHT	FORCE (X)	FORCE (Y)(+)	FORCE (Y)(-)	H/2A	F. COEF (X)	F. COEF (Y)(+)	F. COEF (Y)(-)
3001	0.87	0.41	0.13	0.07	0.22	0.19	0.06	0.03
3002	1.77	0.82	0.30	0.18	0.44	0.38	0.14	0.08
3003	2.59	1.25	0.42	0.24	0.65	0.58	0.19	0.11
3004	3.51	1.58	0.48	0.36	0.88	0.73	0.22	0.17
3005	3.81	1.74	0.54	0.42	0.95	0.81	0.25	0.19

DATA FOR RUN NUMBER 31. TOTAL NUMBER OF RUNS IS 24.

WAVE PERIOD IS 0.634 SECONDS. WAVE LENGTH IS 2.04 FEET. WATER DEPTH IS 11.0 INCHES.

DIMENSIONLESS PARAMETERS ARE 2PIA/GT**2 = 0.9717
2PIA/L = 0.5124
H/L = 0.4485
H/GT**2 = 0.0709

SEGMENT NUMBER	WAVE HEIGHT	FORCE (X)	FORCE (Y)(+)	FORCE (Y)(-)	H/2A	F. COEF (X)	F. COEF (Y)(+)	F. COEF (Y)(-)
3101	0.88	0.30	0.10	0.07	0.22	0.14	0.05	0.03
3102	1.75	0.63	0.24	0.19	0.44	0.29	0.11	0.09
3103	2.55	1.04	0.40	0.33	0.64	0.48	0.19	0.15
3104	2.59	1.12	0.33	0.27	0.65	0.52	0.15	0.12

DATA FOR RUN NUMBER 35. TOTAL NUMBER OF RUNS IS 24.

WAVE PERIOD IS 1.658 SECONDS. WAVE LENGTH IS 7.30 FEET. WATER DEPTH IS 8.0 INCHES.

DIMENSIONLESS PARAMETERS ARE 2PIA/GT**2 = 0.1421
2PIA/L = 0.1434
H/L = 0.0913
H/GT**2 = 0.0075

SEGMENT NUMBER	WAVE HEIGHT	FORCE (X)	FORCE (Y)(+)	FORCE (Y)(-)	H/2A	F. COEF (X)	F. COEF (Y)(+)	F. COEF (Y)(-)
3501	0.36	0.30	0.04	0.0	0.09	0.14	0.02	0.0
3502	0.82	0.72	0.13	0.0	0.20	0.33	0.06	0.0
3503	1.20	0.93	0.21	0.0	0.30	0.43	0.10	0.0
3504	1.79	1.53	0.36	0.0	0.45	0.70	0.17	0.0
3505	2.44	1.91	0.54	0.0	0.61	0.88	0.25	0.0
3506	2.90	2.04	0.48	0.0	0.72	0.94	0.22	0.0

DATA FOR RUN NUMBER 36. TOTAL NUMBER OF RUNS IS 24.

WAVE PERIOD IS 1.259 SECONDS. WAVE LENGTH IS 5.33 FEET. WATER DEPTH IS 8.0 INCHES.

DIMENSIONLESS PARAMETERS ARE 2PIA/GT**2 = 0.2464
2PIA/L = 0.1965
H/L = 0.1251
H/GT**2 = 0.0131

SEGMENT NUMBER	WAVE HEIGHT	FORCE (X)	FORCE (Y)(+)	FORCE (Y)(-)	H/2A	F. COEF (X)	F. COEF (Y)(+)	F. COEF (Y)(-)
3601	0.48	0.52	0.10	0.03	0.12	0.24	0.05	0.01
3602	1.10	1.01	0.27	0.06	0.27	0.47	0.12	0.03
3603	1.53	1.53	0.32	0.18	0.38	0.70	0.15	0.08
3604	2.21	2.07	0.60	0.0	0.55	0.96	0.28	0.0
3605	2.59	2.72	0.78	0.0	0.65	1.26	0.36	0.0
3606	3.66	3.13	0.96	0.0	0.91	1.45	0.44	0.0

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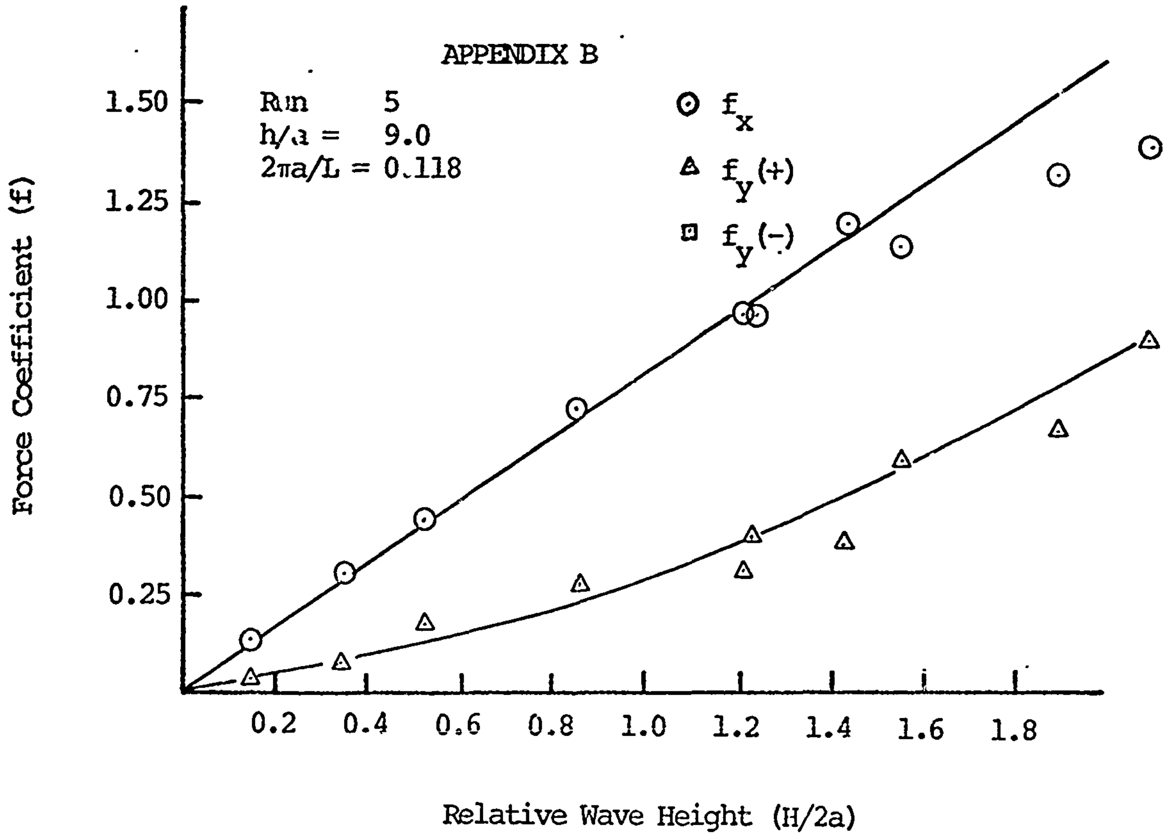
DATA FOR RUN NUMBER 38. TOTAL NUMBER OF RUNS IS 24.

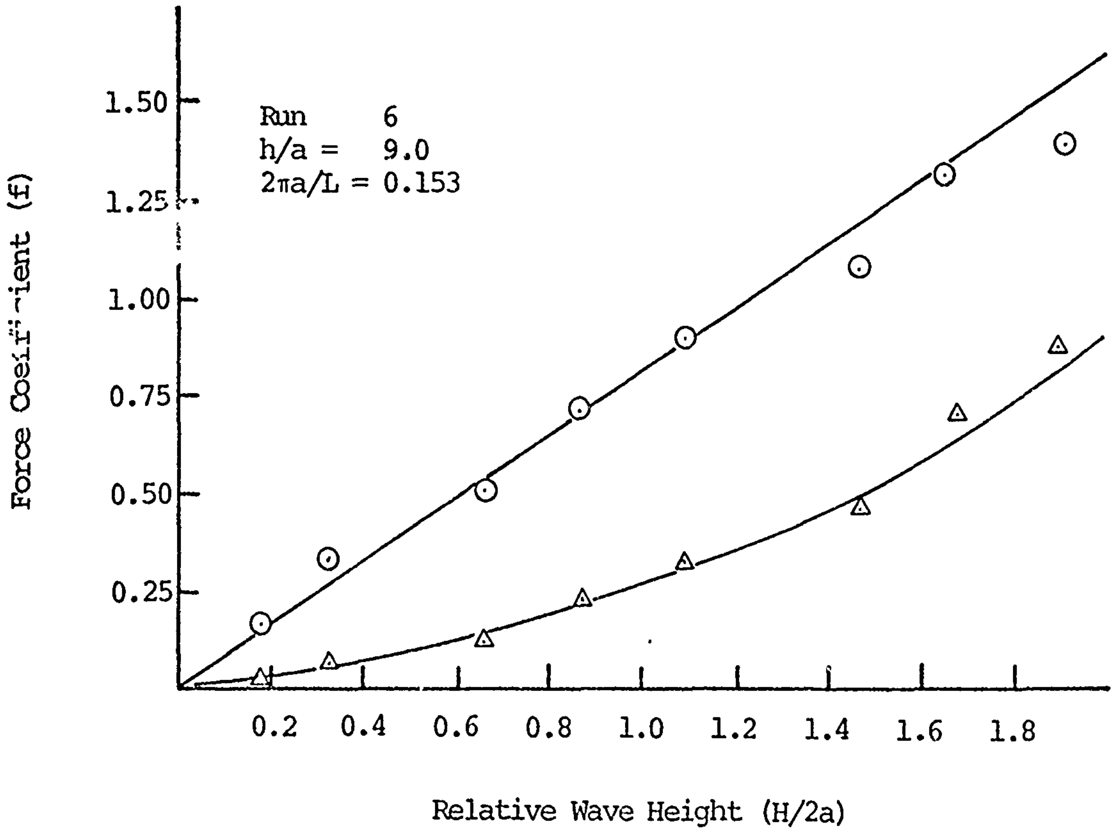
WAVE PERIOD IS 0.724 SECONDS. WAVE LENGTH IS 2.50 FEET. WATER DEPTH IS 8.0 INCHES.

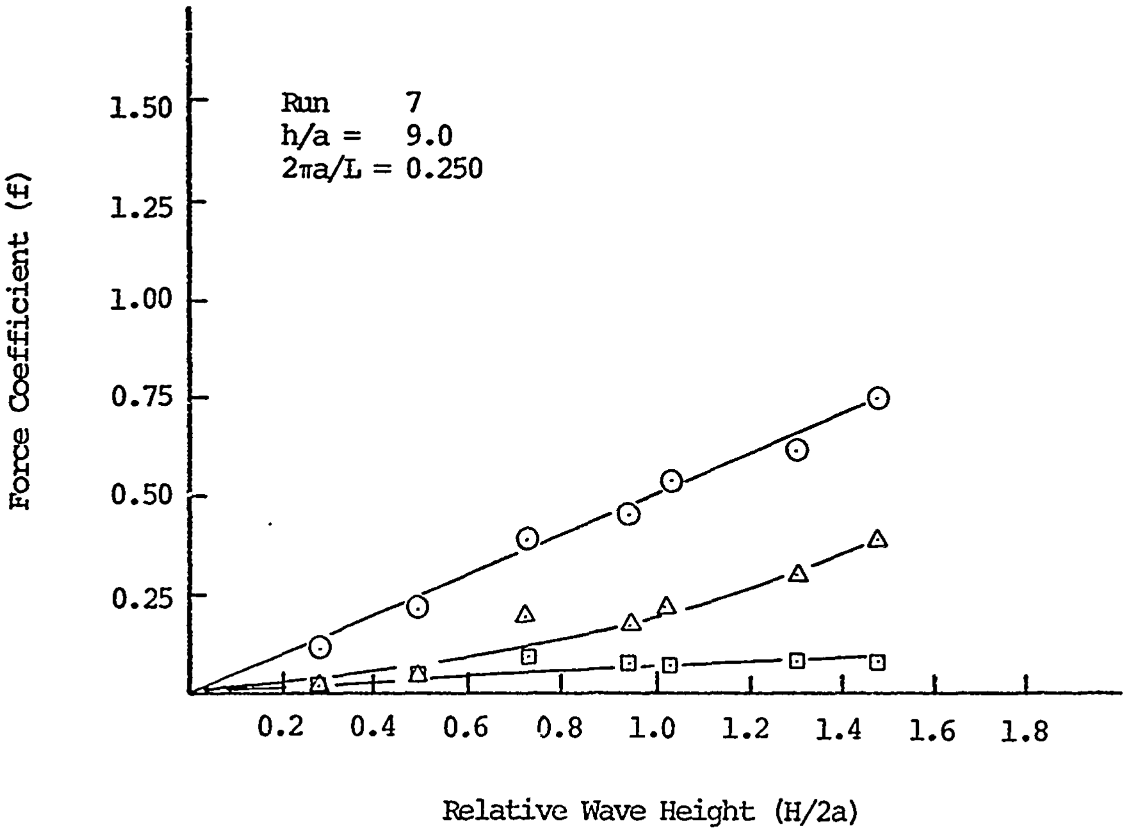
DIMENSIONLESS PARAMETERS ARE 2PIA/GT**2 = 0.7451
2PIA/L = 0.4185
H/L = 0.2664
H/GT**2 = 0.0395

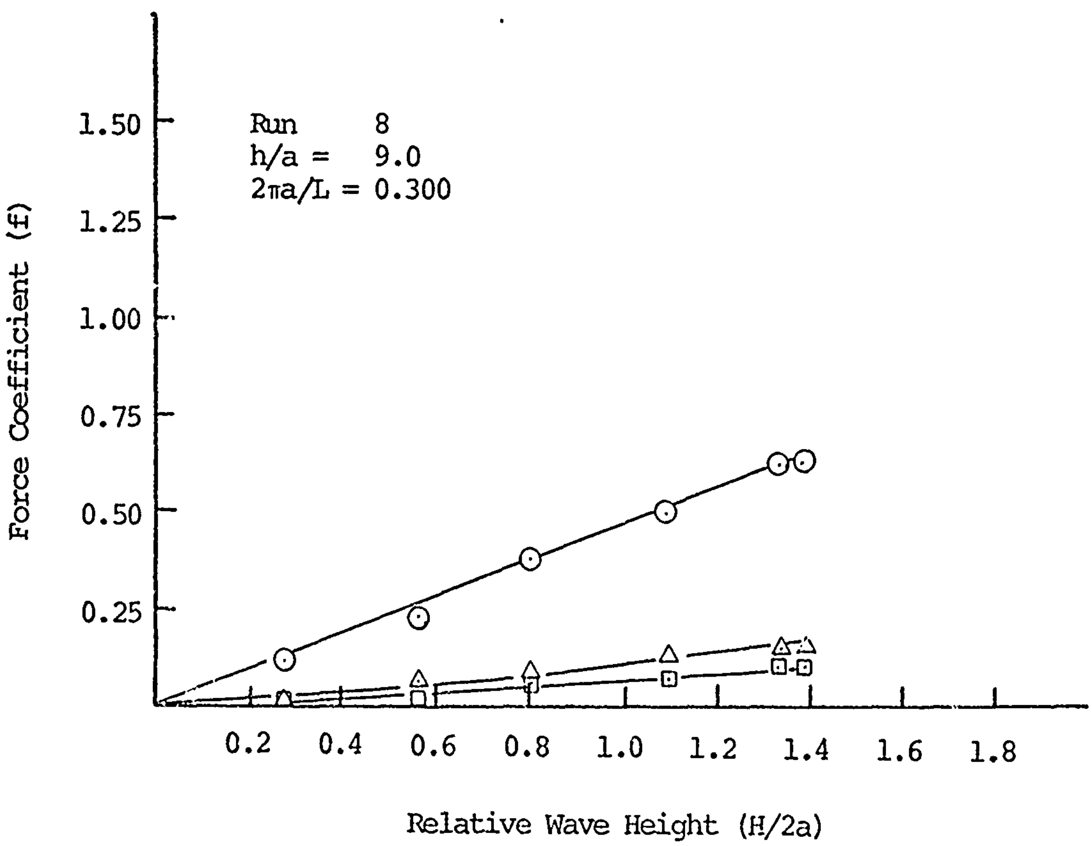
SEGMENT NUMBER	WAVE HEIGHT	FORCE (X)	FORCE (Y)(+)	FORCE (Y)(-)	H/2A	F. COEF (X)	F. COEF (Y)(+)	F. COEF (Y)(-)
3801	0.72	0.57	0.08	0.06	0.18	0.26	0.04	0.03
3802	1.53	1.12	0.36	0.27	0.38	0.52	0.17	0.12
3803	2.36	1.74	0.54	0.48	0.59	0.81	0.25	0.22
3804	3.13	1.91	1.05	0.52	0.78	0.88	0.49	0.24

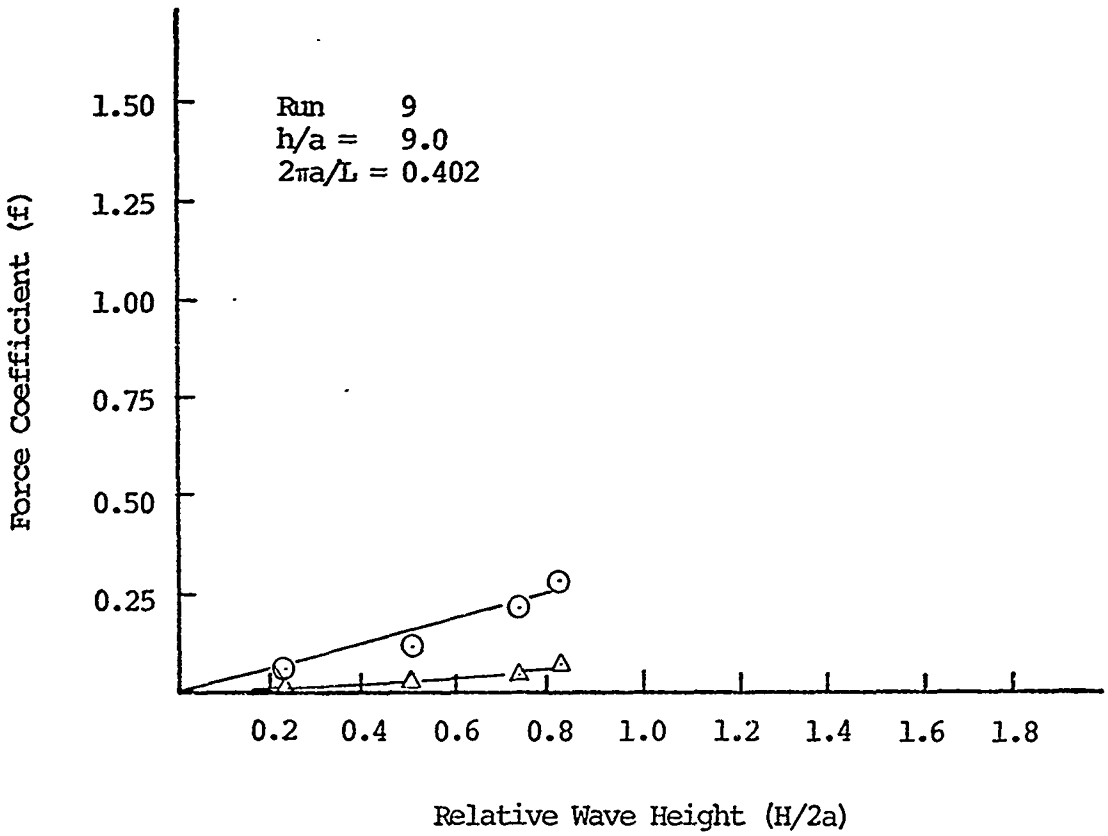
APPENDIX B

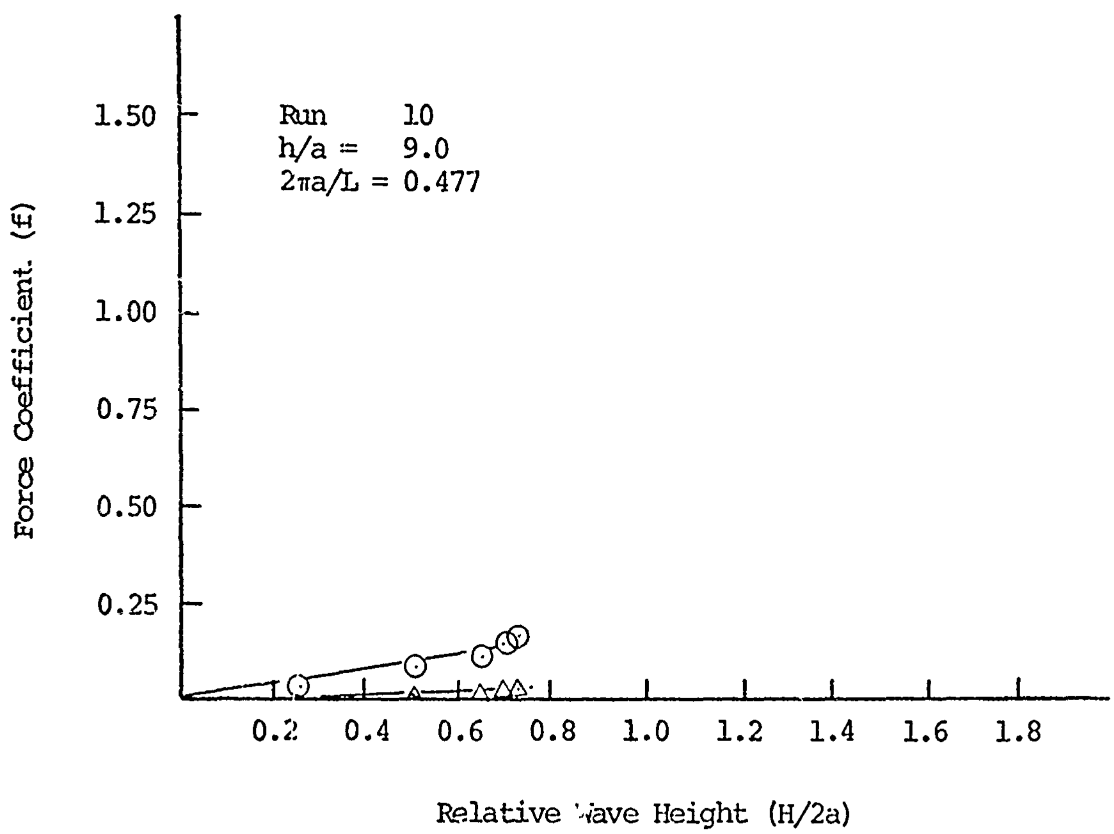

Run 5
h/a = 9.0
2πa/L = 0.118
f_x
f_y(+)
f_y(-)
Force Coefficient (f)
1.50
1.25
1.00
0.75
0.50
0.25
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Relative Wave Height (H/2a)

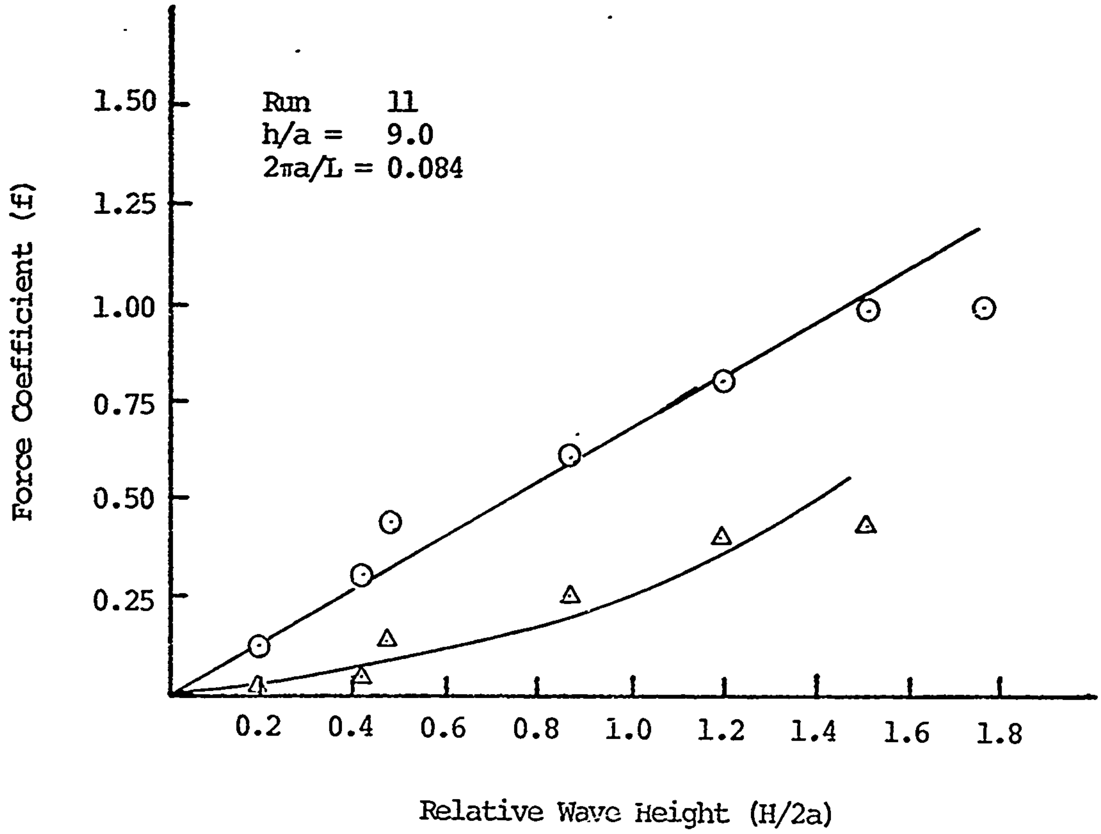

Run 6
h/a = 9.0
2πa/L = 0.153
Force Coefficient (f)
1.50
1.25
1.00
0.75
0.50
0.25
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Relative Wave Height (H/2a)


Run 7
h/a = 9.0
2πa/L = 0.250
Force Coefficient (f)
1.50
1.25
1.00
0.75
0.50
0.25
0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8
Relative Wave Height (H/2a)

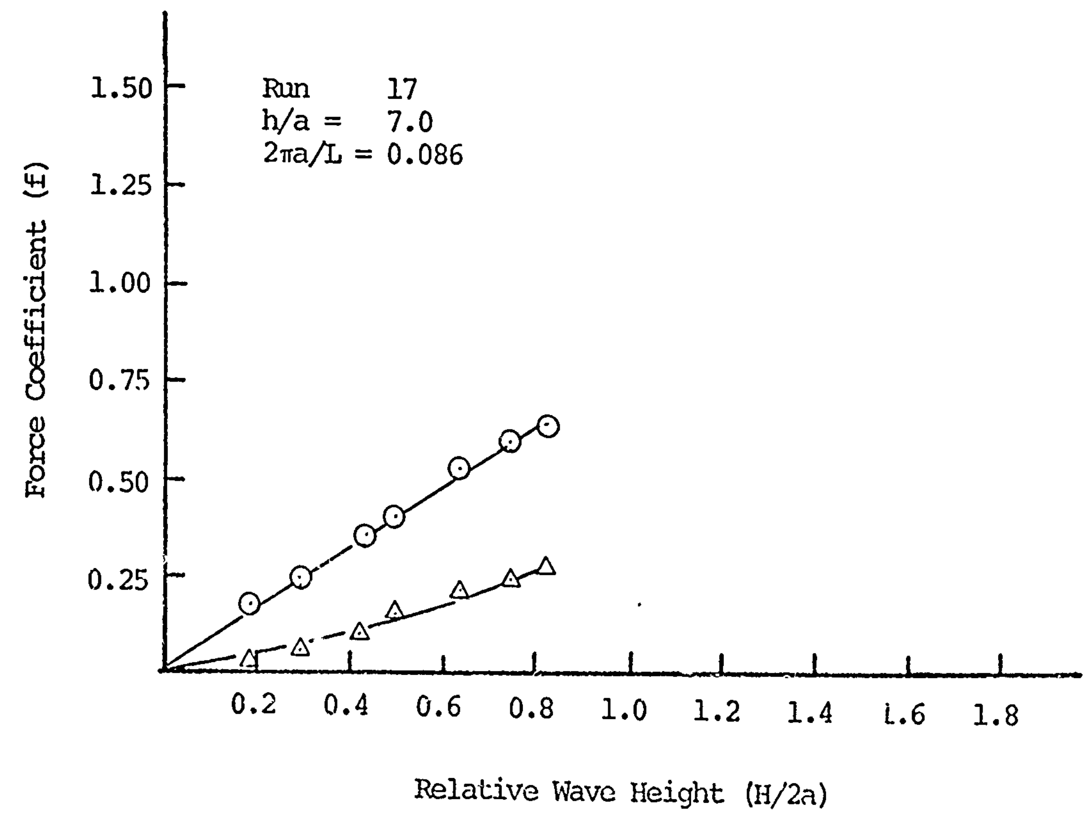

Run 8
h/a = 9.0
2πa/L = 0.300
Force Coefficient (f)
1.50
1.25
1.00
0.75
0.50
0.25
0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8
Relative Wave Height (H/2a)


1.50
1.25
1.00
0.75
0.50
0.25
Force Coefficient (f)
Run 9
h/a = 9.0
2πa/L = 0.402
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Relative Wave Height (H/2a)

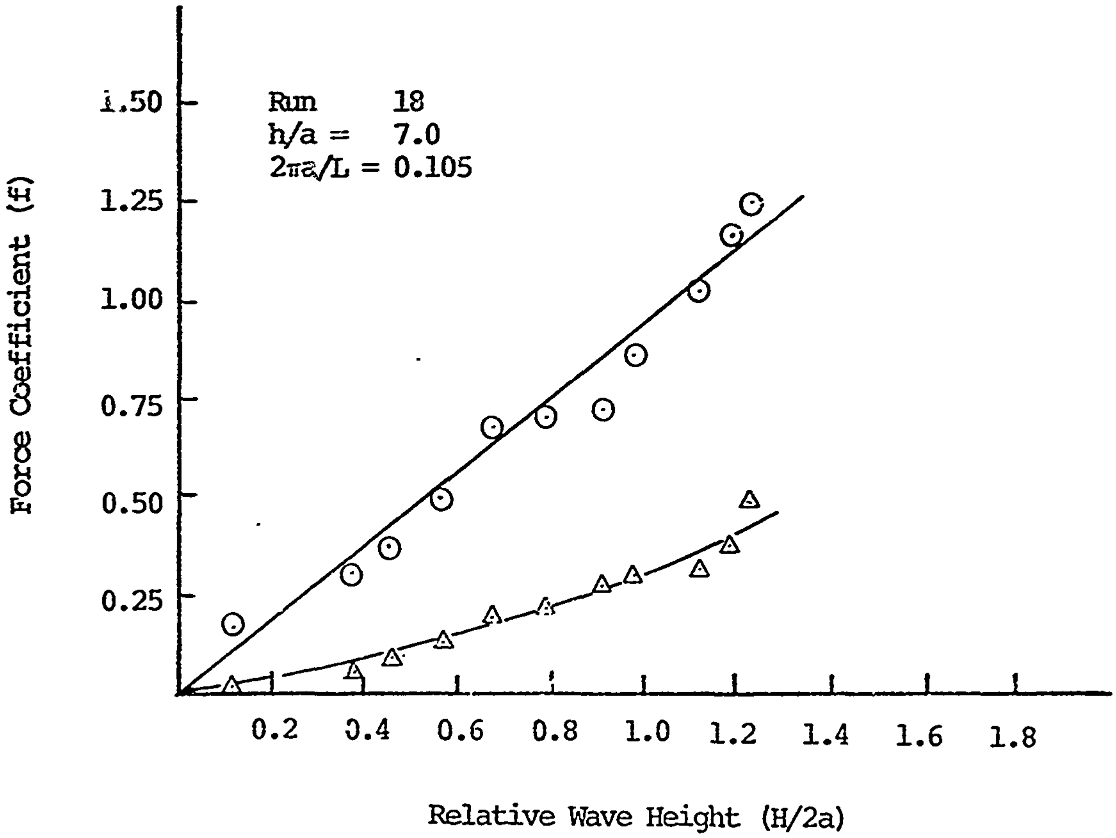

1.50
1.25
1.00
0.75
0.50
0.25
Force Coefficient (f)
Run 10
h/a = 9.0
2πa/L = 0.477
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Relative Wave Height (H/2a)

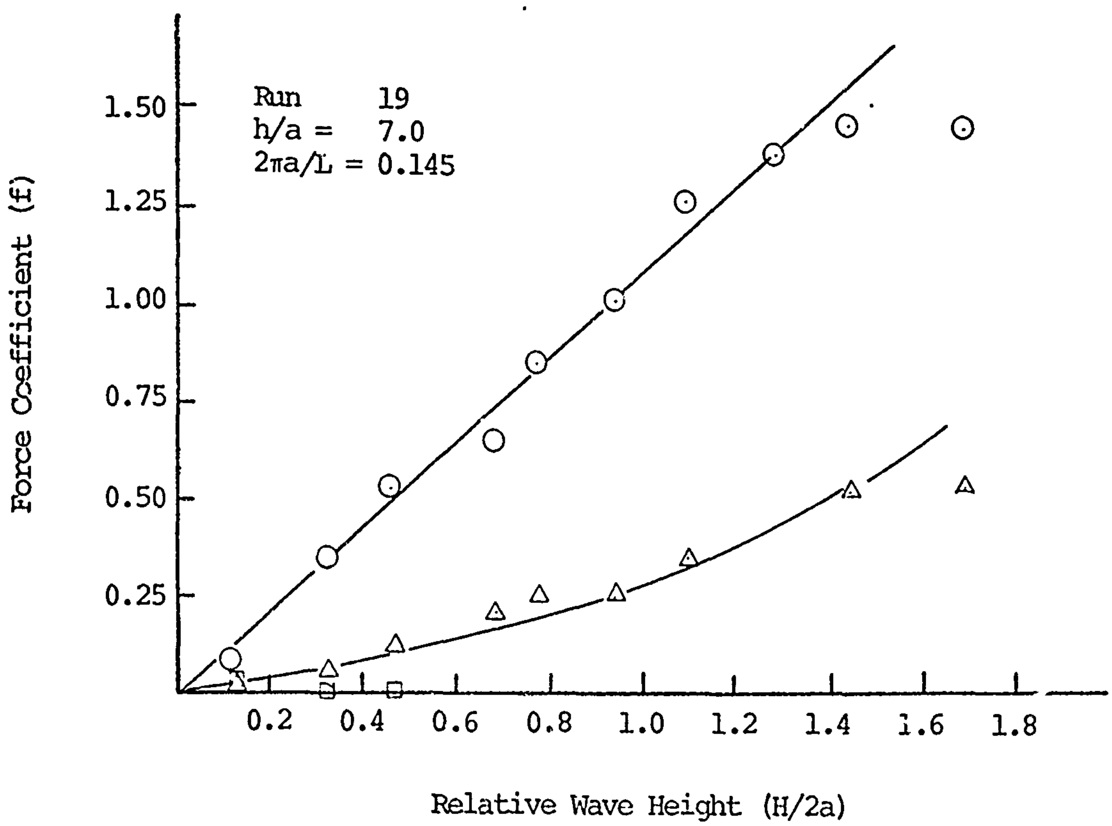


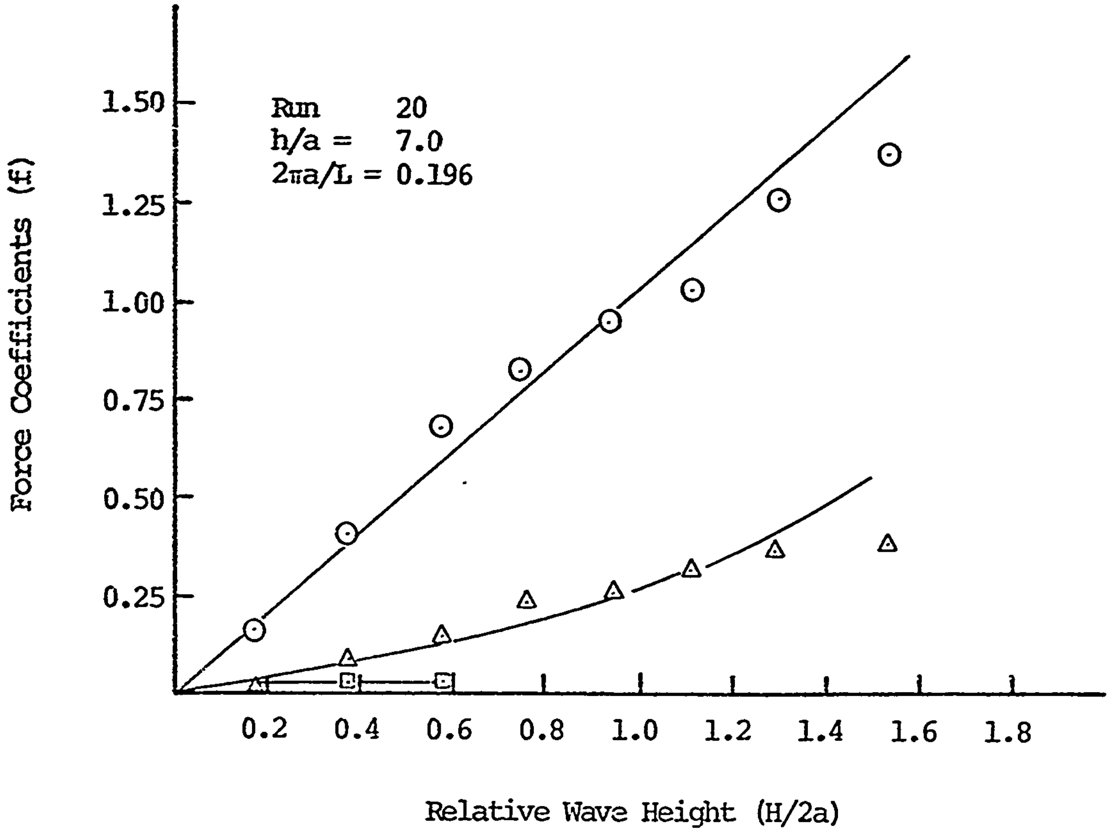
Run 11
h/a = 9.0
2πa/L = 0.084
Force Coefficient (f)
1.50
1.25
1.00
0.75
0.50
0.25
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Relative Wave Height (H/2a)



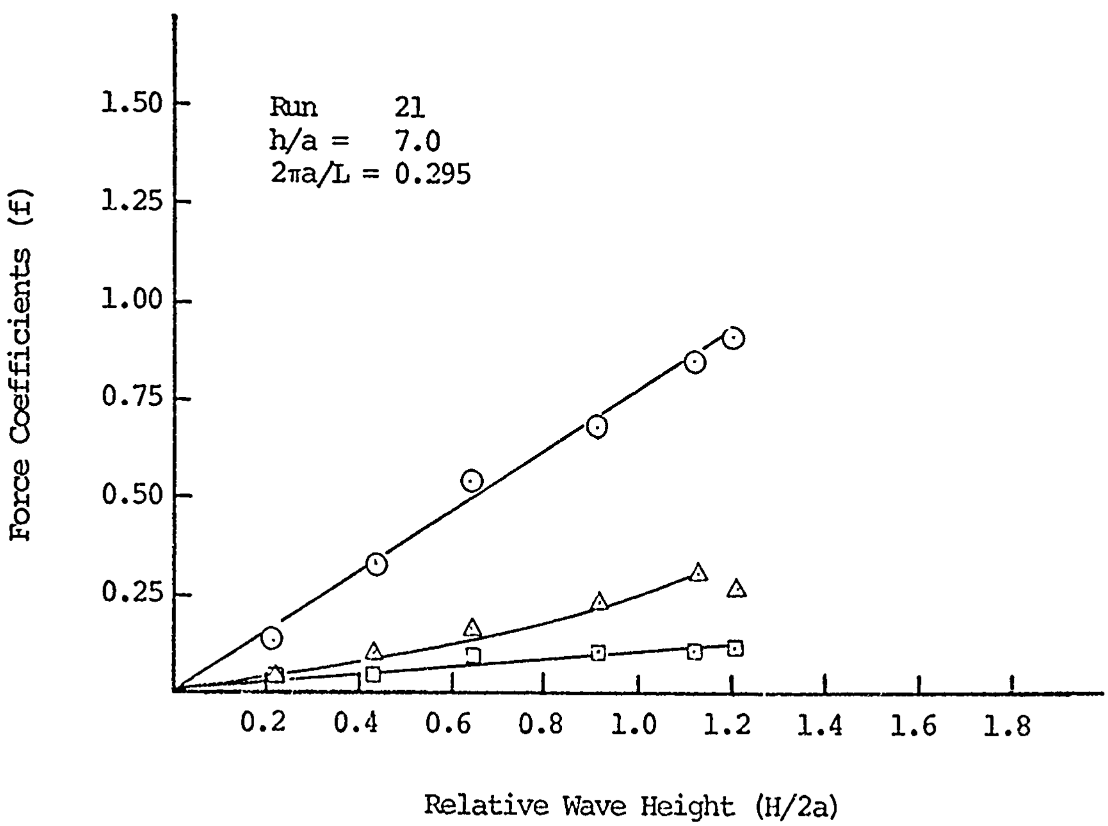
Run 17
h/a = 7.0
2πa/L = 0.086
Force Coefficient (f)
1.50
1.25
1.00
0.75
0.50
0.25
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Relative Wave Height (H/2a)


Run 18
h/a = 7.0
2πa/L = 0.105
Force Coefficient (f)
1.50
1.25
1.00
0.75
0.50
0.25
0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8
Relative Wave Height (H/2a)

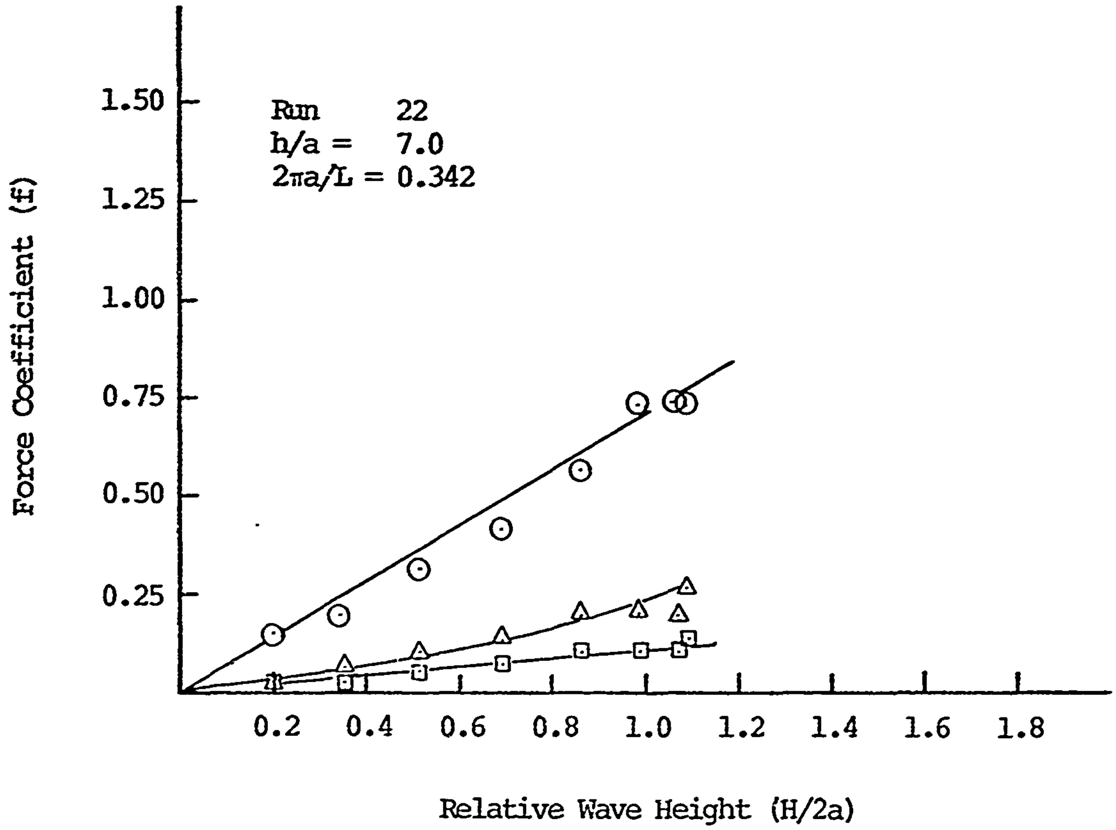

Run 19
h/a = 7.0
2πa/L = 0.145
Force Coefficient (f)
1.50
1.25
1.00
0.75
0.50
0.25
0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8
Relative Wave Height (H/2a)

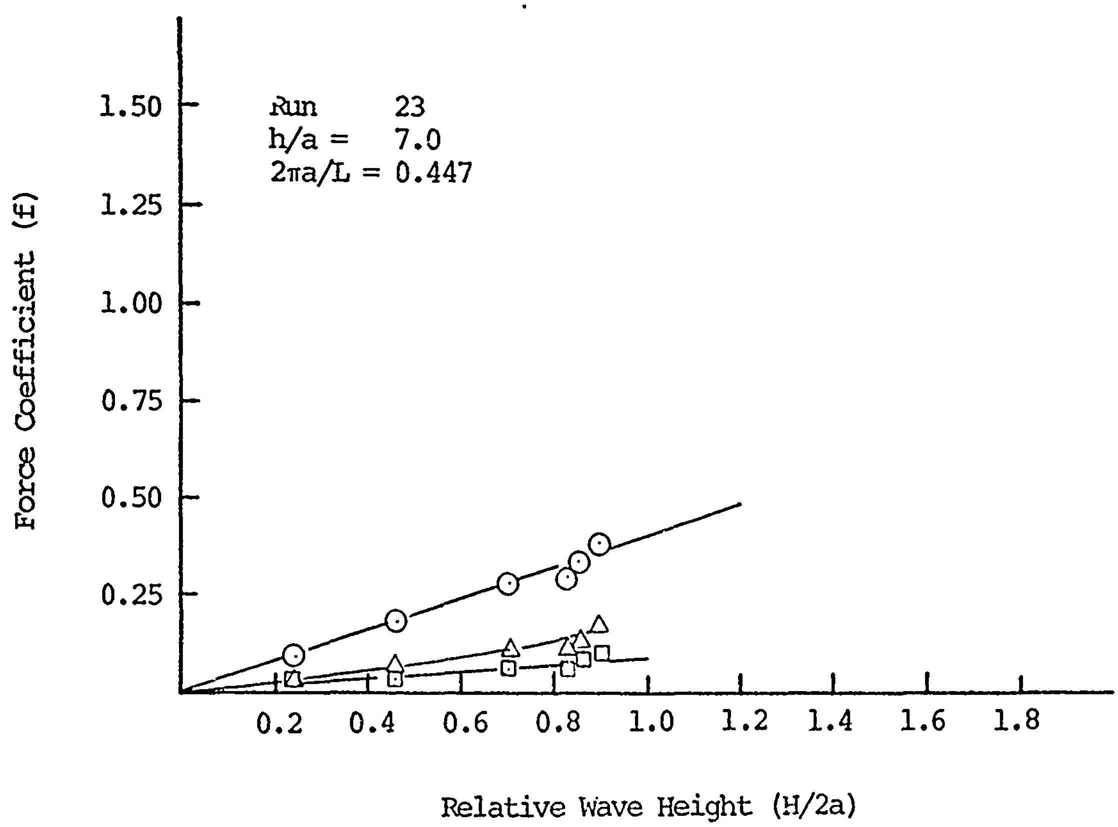


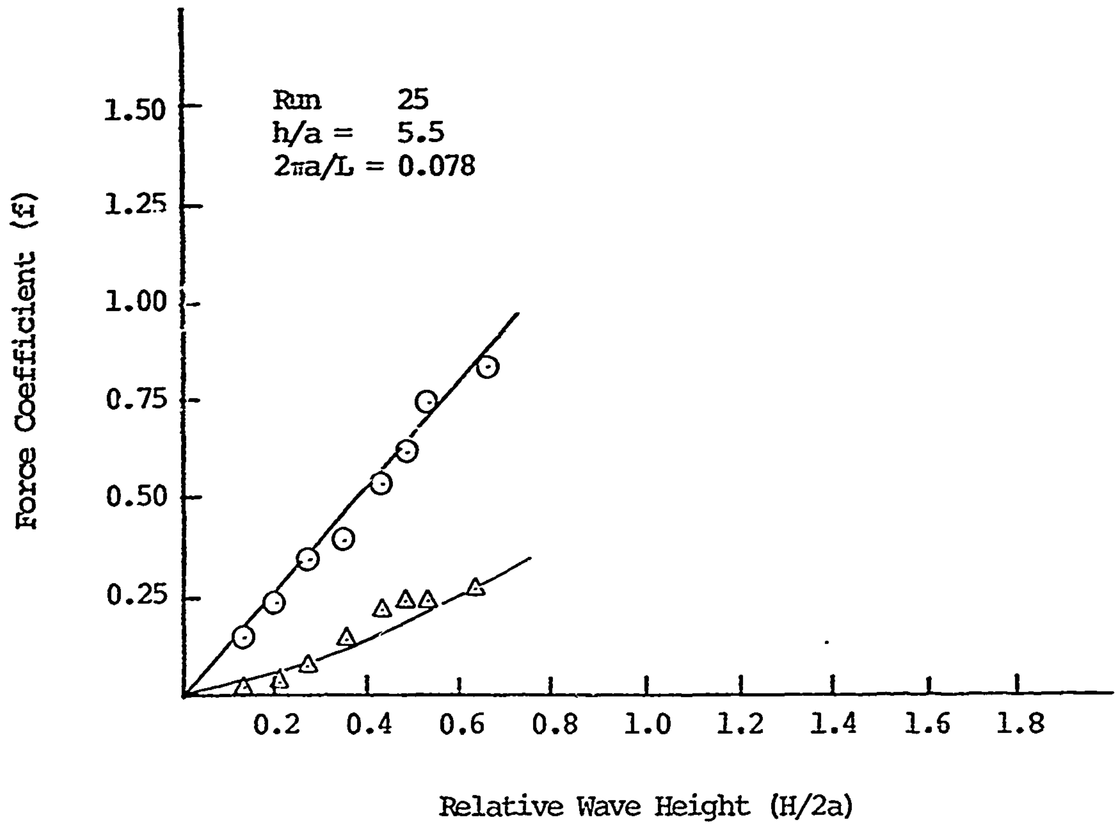
Run 20
h/a = 7.0
2πa/L = 0.196
1.50
1.25
1.00
0.75
0.50
0.25
Force Coefficients (f)
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Relative Wave Height (H/2a)

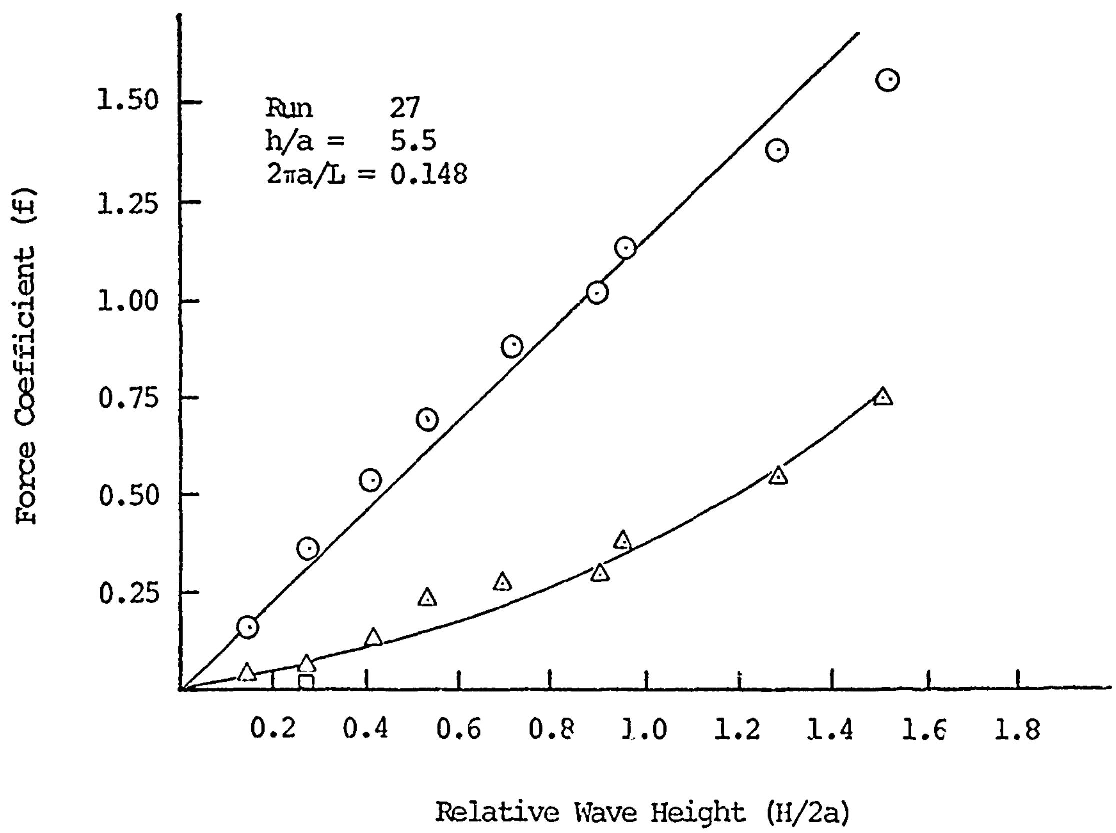


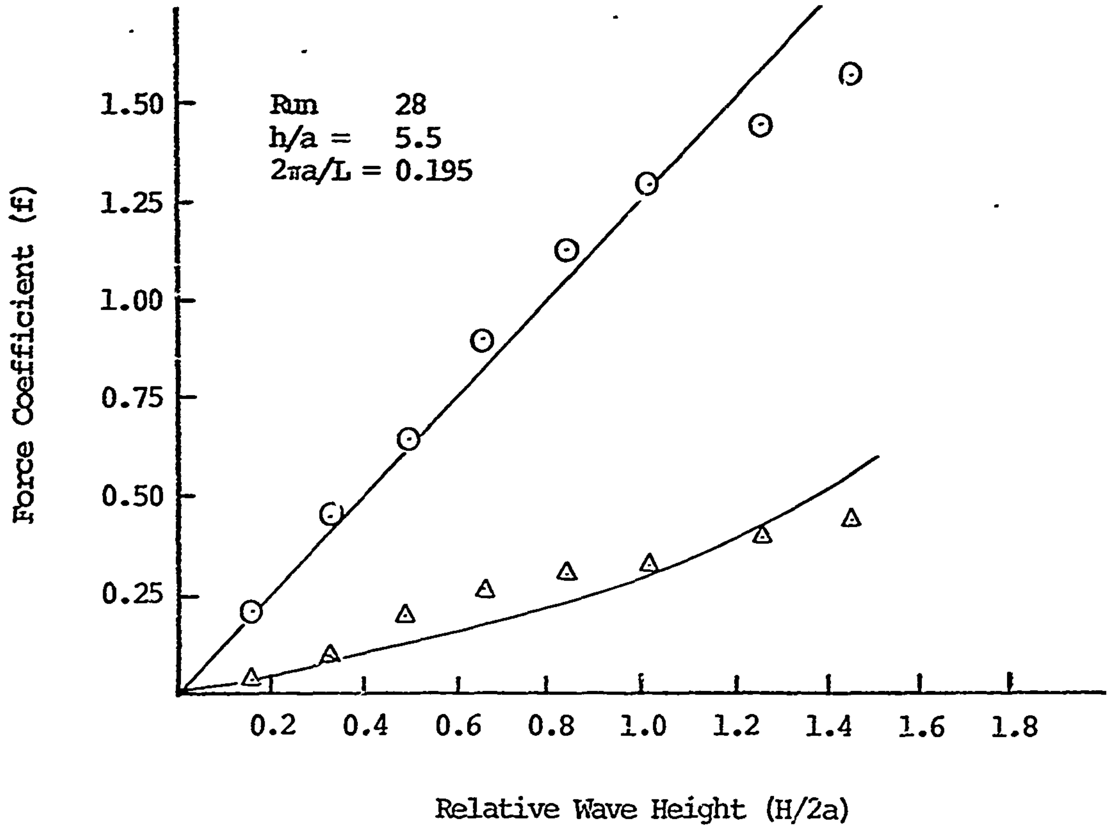
Run 21
h/a = 7.0
2πa/L = 0.295
1.50
1.25
1.00
0.75
0.50
0.25
Force Coefficients (f)
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Relative Wave Height (H/2a)

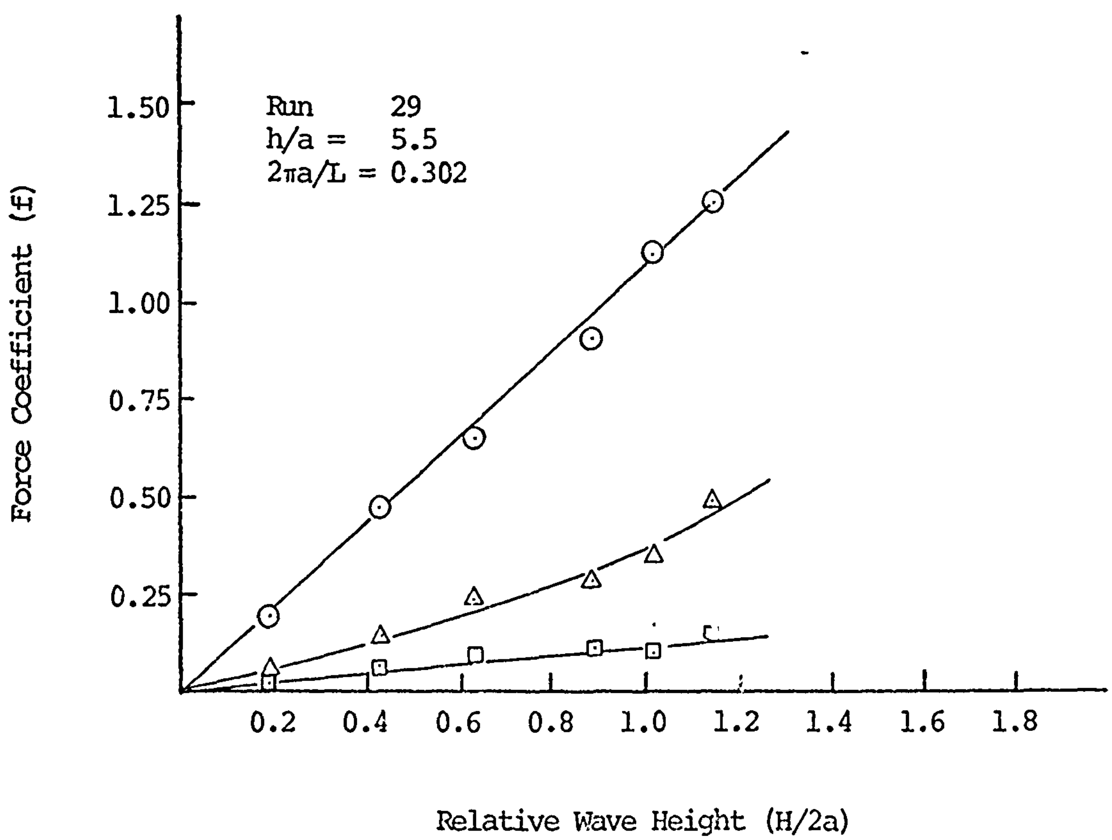

Run 22
h/a = 7.0
2πa/L = 0.342
Force Coefficient (f)
1.50
1.25
1.00
0.75
0.50
0.25
0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8
Relative Wave Height (H/2a)

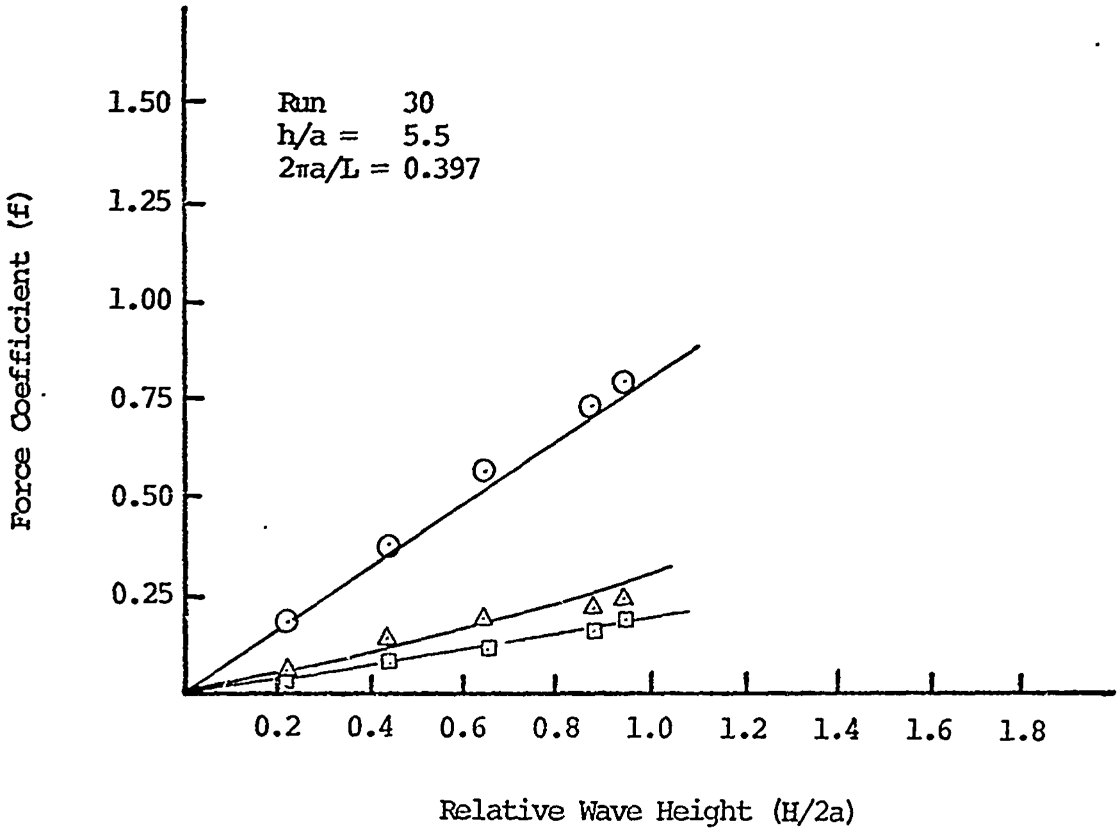

Run 23
h/a = 7.0
2πa/L = 0.447
Force Coefficient (f)
1.50
1.25
1.00
0.75
0.50
0.25
0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8
Relative Wave Height (H/2a)

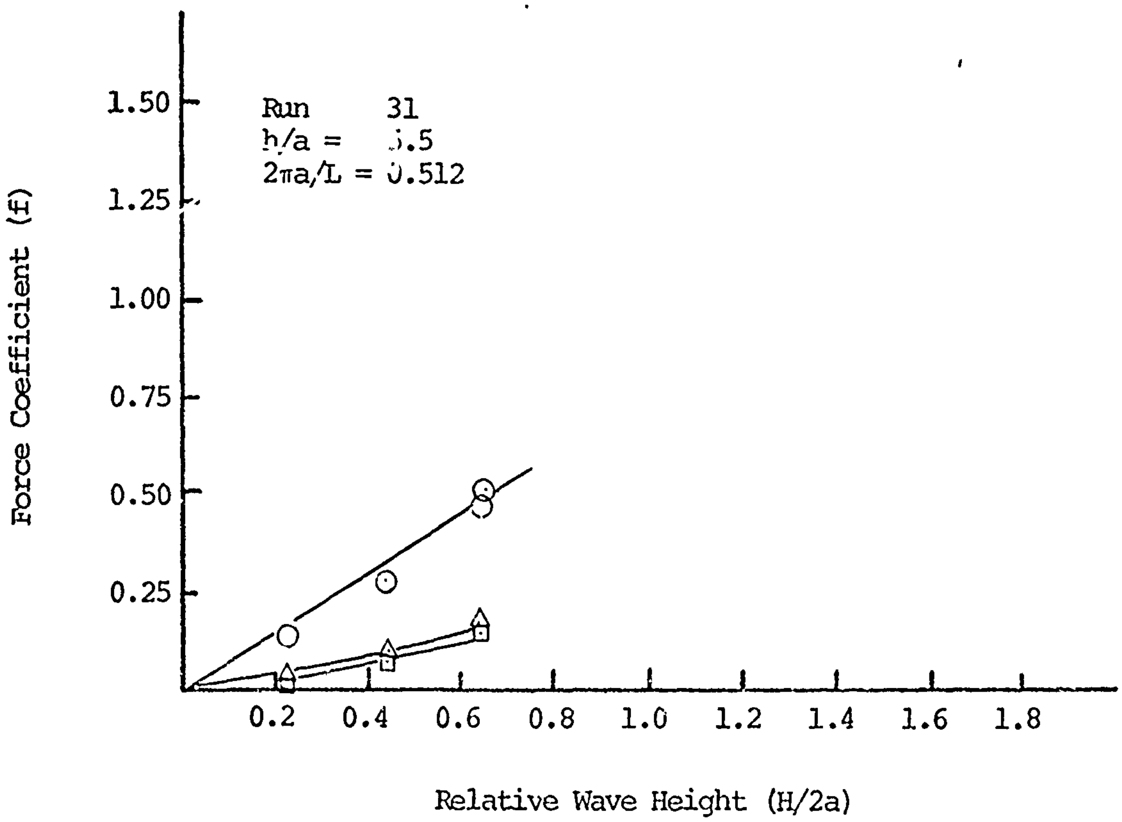

Run 25
h/a = 5.5
2πa/L = 0.078
1.50
1.25
1.00
0.75
0.50
0.25
Force Coefficient (f)
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Relative Wave Height (H/2a)

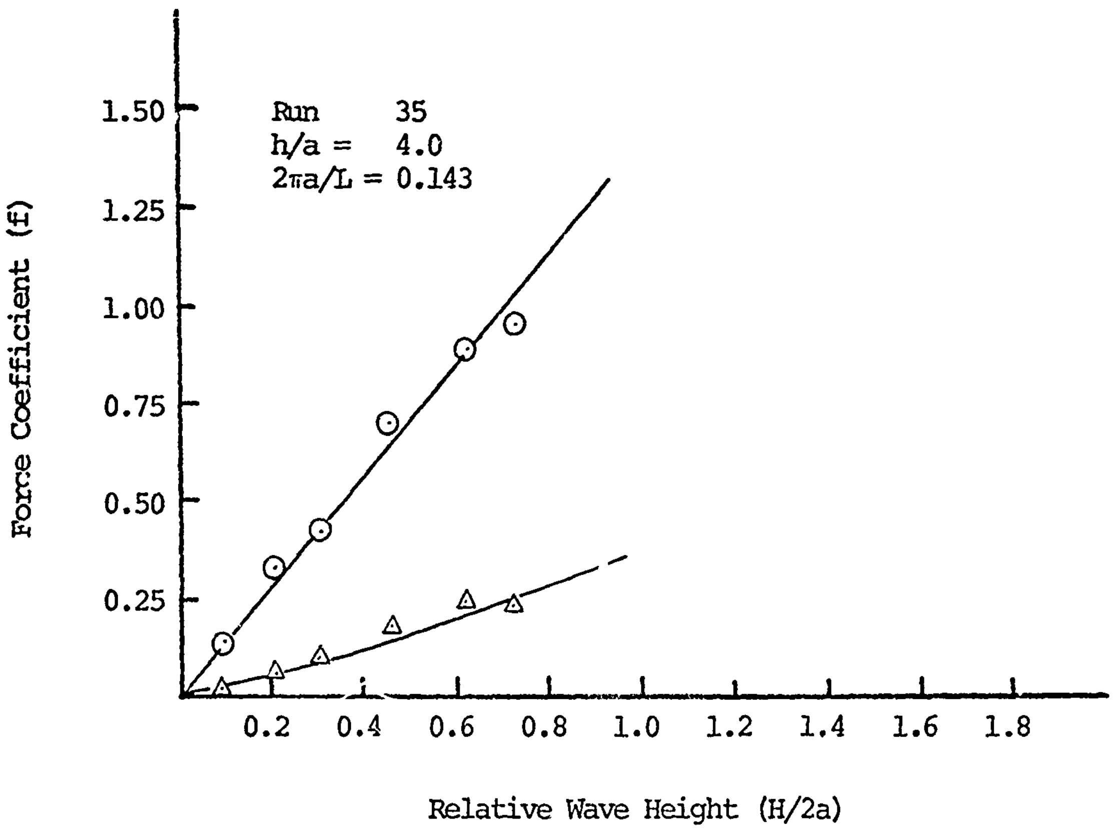

Run 27
h/a = 5.5
2πa/L = 0.148
1.50
1.25
1.00
0.75
0.50
0.25
Force Coefficient (f)
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Relative Wave Height (H/2a)


Run 28
h/a = 5.5
2πa/L = 0.195
1.50
1.25
1.00
0.75
0.50
0.25
Force Coefficient (f)
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Relative Wave Height (H/2a)

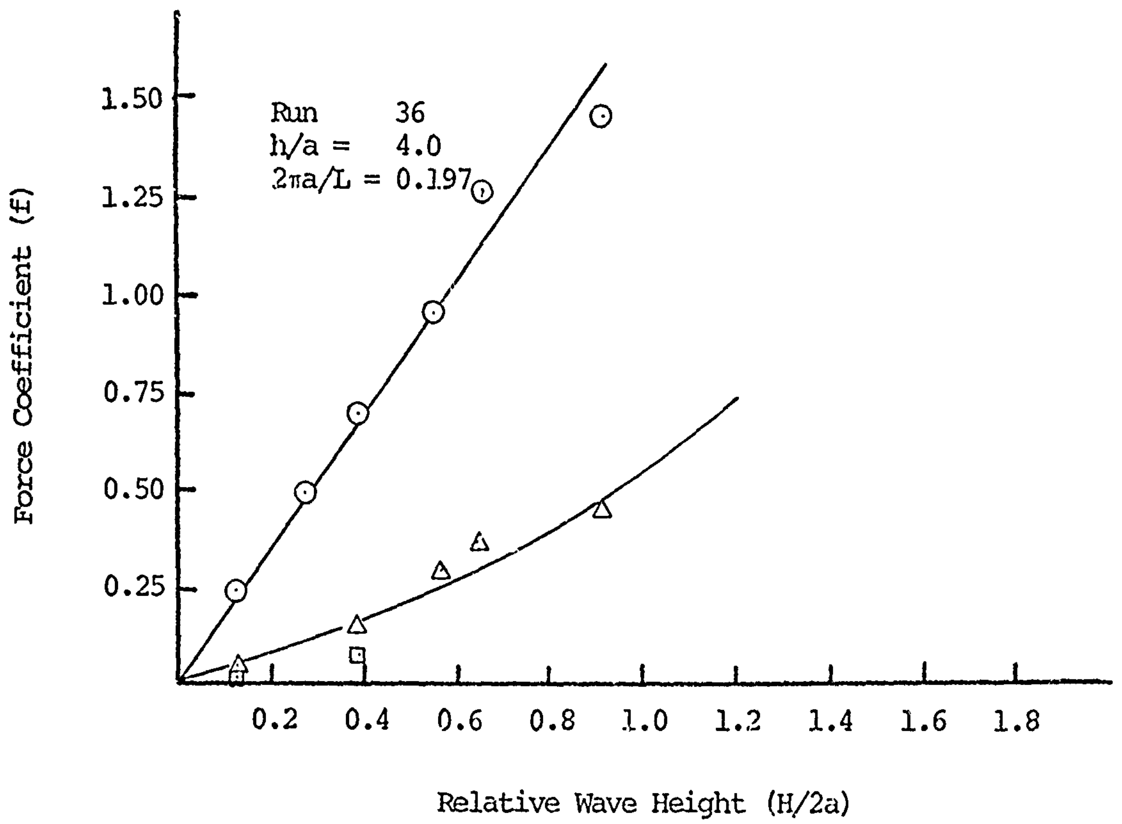

Run 29
h/a = 5.5
2πa/L = 0.302
1.50
1.25
1.00
0.75
0.50
0.25
Force Coefficient (f)
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Relative Wave Height (H/2a)


Run 30
h/a = 5.5
2πa/L = 0.397
Force Coefficient (f)
1.50
1.25
1.00
0.75
0.50
0.25
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Relative Wave Height (H/2a)

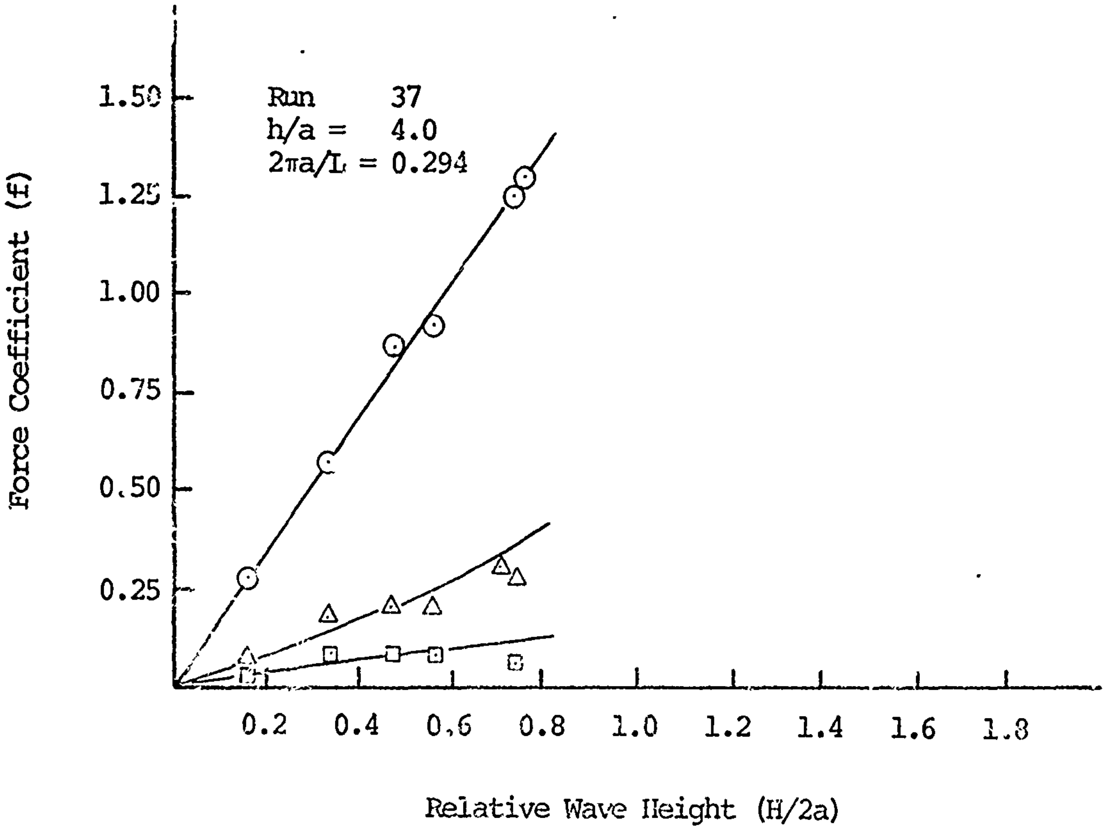

Run 31
h/a = 5.5
2πa/L = 0.512
Force Coefficient (f)
1.50
1.25
1.00
0.75
0.50
0.25
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Relative Wave Height (H/2a)

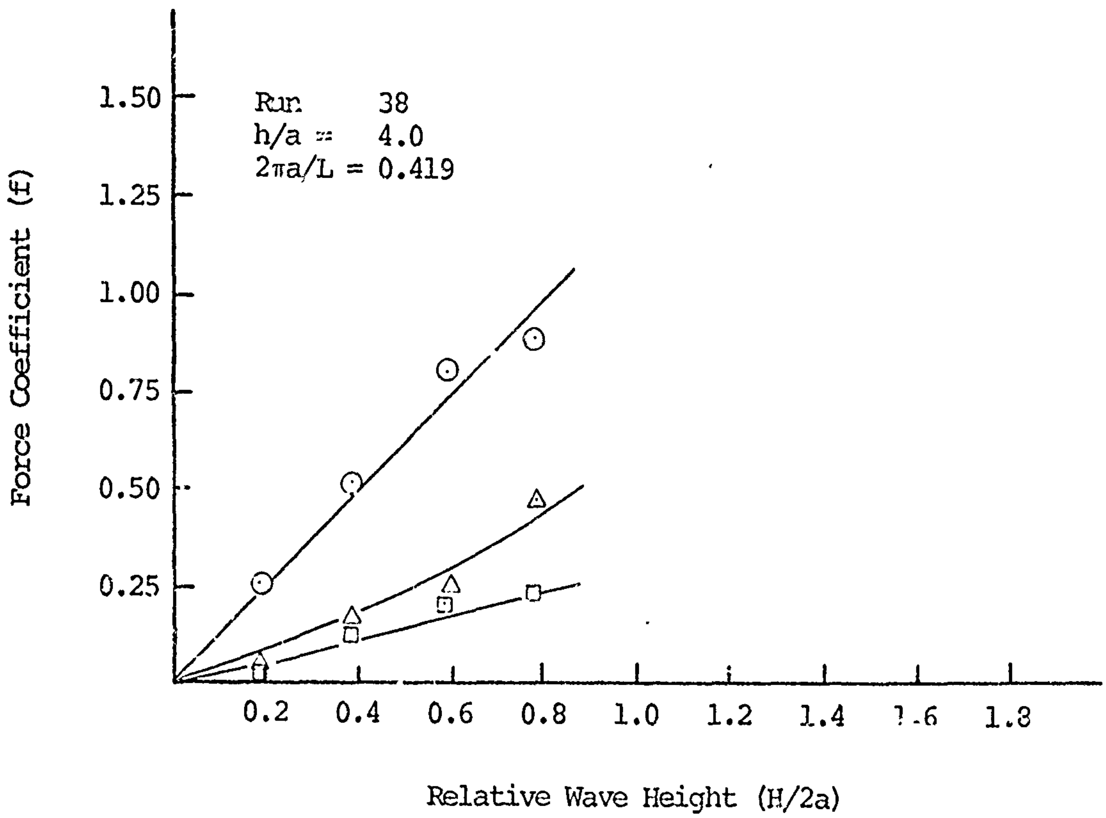


Run 35
h/a = 4.0
2πa/L = 0.143
Force Coefficient (f)
1.50
1.25
1.00
0.75
0.50
0.25
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Relative Wave Height (H/2a)



Run 36
h/a = 4.0
2πa/L = 0.197
Force Coefficient (f)
1.50
1.25
1.00
0.75
0.50
0.25
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Relative Wave Height (H/2a)


Run 37
h/a = 4.0
2πa/L = 0.294
Force Coefficient (f)
1.50
1.25
1.00
0.75
0.50
0.25
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Relative Wave Height (H/2a)


Run 38
h/a = 4.0
2πa/L = 0.419
Force Coefficient (f)
1.50
1.25
1.00
0.75
0.50
0.25
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Relative Wave Height (H/2a)

APPENDIX C

```
WAVE FORCES ON A HORIZONTIAL CIRCULAR CYLINDER

THESIS TOPIC                     BRIAN T. PERKINSON

NAVAL POSTGRADUATE SCHOOL                 JUNE 1972

CLGTH IS THE CYLINDER LENGTH RECORDED IN INCHES.
CRAD IS THE CYLINDER RADIUS IN INCHES.
NRUNS IS THE NUMBER OF RUNS REDUCED.
NRUN IS THE RUN NUMBER.
NSEGS IS THE NUMBER OF SEGMENTS PER RUN.
NSEG IS THE SEGMENT NUMBER.
DEPTH IS WATER DEPTH RECORDED IN INCHES.
PERIOD IS THE WAVE PERIOD IN SECONDS.
DP1 IS A DIMENSIONLESS PARAMETER RATIO OF CYLINDER CIRCUMFERENCE
     TO THE PRODUCT OF G AND THE PERIOD SQUARED.
DP2 IS A DIMENSIONLESS PARAMETER RATIO OF CYLINDER CIRCUMFERENCE
     TO WAVE LENGTH.
DP3 IS A DIMENSIONLESS PARAMETER RATIO OF WATER DEPTH TO WAVE LENGTH.
DP4 IS THE RATIO OF THE WATER DEPTH TO THE PRODUCT OF G AND THE
     PERIOD SQUARED.
DP5 IS THE RATIO OF THE WAVE HEIGHT TO THE CYLINDER DIAMETER.
SIGMAP IS THE PREDICTED VALUE OF WAVE FREQUENCY.
SIGMAC IS THE CORRECTED VLAUE OF WAVE FREQUENCY.
WVNR IS THE WAVE NUMBER.
WL IS WAVE LENGTH IN FEET.
WHGT IS THE WAVE HEIGHT RECORDED IN INCHES.
FXMAX IS THE MAXIMUM HORIZONTAL FORCE IN POUNDS.
FYUMAX IS THE MAXIMUM VERTICAL FORCE UP RECORDED IN POUNDS.
FYDMAX IS THE MAXIMUM VERTICAL FORCE DOWN RECORDED IN POUNDS.
FCX IS THE HORIZONTAL FORCE COEFFICIENT.
FCYU IS THE VERTICAL FORCE COEFFICIENT UP.
FCYD IS THE VERTICAL FORCE COEFFICIENT DOWN.

DATA PI/3.1415926/,EPS/0.001/,G/32.175/
READ (5,20) NRUNS,CLGTH,CRAD
DO 58 I=1,NRUNS
READ (5,30) NRUN,NSEGS,DEPTH,PERIOD
DP1=2*PI*CRAD/(PERIOD**2*G)
SIGMAP=DP1*2*PI/CRAD
WVNR=SIGMAP
DO 43 J=1,200
SIGMAC=WVNR*  TANH(WVNR*DEPTH/12.0)
WVNR=WVNR+0.5*(SIGMAP-SIGMAC)
```

```
      IF (ABS(SIGMAP-SIGMAC).LT.EPS) GO TO  44
   43 CONTINUE
   44 WL=2.0*PI/WVNR
      DP2=2*PI*CRAD/(WL*12.0)
      DP3=DEPTH/(WL*12.0)
      DP4=DEPTH/(12.0*G*PERIOD**2)
      WRITE (6,48) NRUN,NRUNS,PERIOD,WL,DEPTH,DP1,DP2,DP3,DP4
      WRITE (6,49)
      DO 58 K=1,NSEGS
      READ (5,50) NSEG, WHGT, FXMAX,FYUMAX,FYDMAX
      FCX=27.7145*FXMAX/(CLGTH*CRAD**2)
      FCYU=27.7145*FYUMAX/(CLGTH*CRAD**2)
      FCYD=27.7145*FYDMAX/(CLGTH*CRAD**2)
      DP5=WHGT/(2*CRAD)
      WRITE (6,57) NSEG,WHGT,FXMAX,FYUMAX,FYDMAX,DP5,FCX,FCYU,FCYD
   58 CONTINUE
   20 FORMAT (I10,2F10.5)
   30 FORMAT (2I10,2F10.5)
   48 FORMAT ('1',/////,11X,'DATA FOR RUN NUMBER',I3,'.',2X,'TOTAL NUMBE
     1R OF RUNS IS',I3,'.',//,' ',10X,'WAVE PERIOD IS',F7.3,' SECONDS.
     2WAVE LENGTH IS',F6.2,' FEET.  WATER DEPTH IS',F5.1,' INCHES.',//,'
     3 ',10X,'DIMENSIONLESS PARAMETERS ARE 2PIA/GT**2 =',F7.4,/,' ',43X,
     4'2PIA/L =',F7.4,/,' ',46X,'H/L =',F7.4,/,' ',42X,'H/GT**2 =',F7.4,
     5////)
   49 FORMAT (' ',10X,'SEGMENT',3X,'WAVE',5X,'FORCE',3X,'FORCE',4X,'FORC
     1E',4X,'H/2A',3X,'F. COFF',3X,'F. COEF',3X,'F. COEF',/,' ',10X,'NUM
     2BER',4X,'HEIGHT',4X,'(X)',4X,'(Y)(+)',3X,'(Y)(-)',10X,'(X)',7X,'(Y
     3)(+)',4X,'(Y)(-)',//)
   50 FORMAT (I10,20X,6F10.4)
   57 FORMAT (' ',12X,I4,5X,F4.2,5X,F4.2,4X,F4.2,5X,F4.2,4X,F4.2,5X,F4.2
     1,5X,F4.2,6X,F4.2)
      STOP
      END
```

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